#### 1 STATE OF NEW MEXICO 2 BEFORE THE ENVIRONMENTAL IMPROVEMENT BOARD 3 4 5 IN THE MATTER OF PROPOSED NEW REGULATION, 6 20.2.350 NMAC – Greenhouse Gas Cap and Trade Provisions No. EIB 10-04 (R) 7 8 9 10 11 TESTIMONY OF DAVID S. GUTZLER, PhD 12 13 14 15 My name is David S. Gutzler. I am a climate scientist and professor at the University of New Mexico. I have a PhD in Meteorology and I have authored or co-authored numerous 16 17 published reports and studies on the topic of climate variability and change. Since joining the 18 faculty of UNM much of my research has focused on the climate of southwestern North 19 America. 20 My written testimony is summarized from the following studies that I led or participated 21 in: (1) David S. Gutzler, Climate Change and Water Resources in New Mexico, in New Mexico 22 Earth Matters (New Mexico Bureau of Geology and Mineral Resources, Summer 2007) (NMED-23 Gutzler Exhibit 1); (2) The Impact of Climate Change on New Mexico's Water Supply and 24 Ability to Manage Water Resources (NMOSE/ISC, July 2006) ("Water Impact Study") (NMED-25 Gutzler Exhibit 2); (3) David S. Gutzler and Tessia O. Robbins, Climate Variability and 26 Projected Change in the Western United States: Regional Downscaling and Drought Statistics 27 (June 2010, DOI 10.1007/s00382-010-0838-7, 2010 ("Drought Study") (NMED-Gutzler Exhibit 28 3); and (4) Thomas L. Kennedy, David S. Gutzler, Ruby L. Leung, Predicting future threats to

the long-term survival of Gila trout using a high-resolution simulation of climate change (Sept.

2008, DOI 10.1007/s10584-008-9503-0) ("Gila Trout Study") (NMED-Gutzler Exhibit 4). I

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- summarize these studies and incorporate into my testimony by reference the full text set out in
- 2 these studies. My testimony concludes with a discussion of the recommendations I can make
- 3 based on my studies of climate variability and change in southwestern North America.

#### I. INTRODUCTION

The purpose of my testimony is to describe, briefly but to the best of my ability, the evidence of potential climate change and the scope and magnitude of the impacts of this potential climate change for the State of New Mexico. Upward temperature trends are already clearly observed in New Mexico. Projections of future climate in the 21st Century, based on a plausible 'mid-range' greenhouse gas emissions scenario, include very significant trends toward conditions that would be much warmer than any instrumental observations made in the 20th Century. In a semiarid climate such as New Mexico's, such warming would shift the surface water balance toward much drier conditions. Streamflows in the state's major rivers are projected to decrease, caused by diminished snowpack and higher rates of evaporation in a warmer climate. Stresses on water supplies in the state associated with long-term climate change will be multiplied by other, non-climatic effects such as population growth and depletion of groundwater supplies, and the long-term changes in climate will be greatly exacerbated during years or decades of drought.

Most of my testimony focuses on regional climate change, but I will state at the outset that the results of my studies of regional climate are entirely consistent with continental and global climate variability and change that have been analyzed by many other scientists. The strength and diversity of evidence for the reality of human-caused climate change is demonstrated by the overwhelming consensus on this issue expressed by the international scientific community through the Intergovernmental Panel on Climate Change (IPCC). Until this year I have not formally been involved in the development of IPCC reports. My own

1 independent research leads me to concur with the general conclusions reached to date by the

2 IPCC. Earlier this year I was nominated to the IPCC by the U.S. Global Change Research

3 Program to become a lead author for one of the chapters in the next major IPCC climate change

assessment, scheduled for publication three years from now. In June 2010 I accepted an

invitation from the IPCC to join the writing team for their 2013 Fifth Assessment Report.

The scientific validity of the IPCC's assessments has been affirmed by numerous independent scientific societies. In the United States, climate change statements confirming the reality of current climate change and the attribution of current change to increasing greenhouse gases of anthropogenic origin have been issued by many such groups, including the following statements that are appended to this testimony as NMED-Gutzler Exhibit 5:

- American Association for the Advancement of Science (AAAS) (February 2007)
- 12 American Meteorological Society (February 2007)
- American Physical Society (November 2007, with Commentary added April 2010)
- 14 American Geophysical Union (December 2007)
- Geological Society of America (April 2010)

In addition, the AAAS sponsored a letter to the United States Senate in October 2009 signed by leaders of 18 separate scientific organizations affirming the reality and severity of ongoing and projected climate change. It is important for the EIB to understand that claims of uncertainty and ongoing scientific debate about the most basic results of climate change science fly in the face of a mountain of diverse scientific evidence, vetted by hundreds of climate scientists, and endorsed by dozens of the foremost independent scientific societies in this country and abroad.

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#### 1. Climate Change and Water Resources in New Mexico

#### a. Our Climate is Warming.

New Mexico's climate, as defined in terms of decadal averages of daily weather, is now warmer than at any time during the past century, the period for which we have instrumental temperature records. The time series of statewide average temperature for both the cold half of the year (October through March) and the warm half (April through September) suggests some cooling during the initial decades of the 20th century. The 1950s drought years were characterized by higher temperatures, especially in the warm season. Rapid warming has occurred year-round since the 1960s and continues today—with an increase of almost 2°F in the cold season and nearly 3°F in the warm season since that time. The year-to-year variability of temperature is still large, so we do not expect to see every year warmer than the previous year. Nevertheless the temperature trends across the Southwest that have been observed over the late 20th Century are raising decade-average temperature up to a level that is significantly different than it was earlier in the instrumental record.

These warming trends are more than twice the annual global average trend, which was about 1°F over the entire 20th century. This is consistent with the expectation that continental temperature should exhibit larger climate changes than oceanic temperatures, which tend to dominate global averages because oceans cover more than 70% of our planet.

The ongoing warming trend in New Mexico is quite significant already. Utility companies measure annual heating requirements using "heating degree days" (HDDs), a measure that relates each day's temperature to the demand for energy for heating. These values are used by state regulators in setting gas rates, so the average annual HDD accumulation is an important economic index of climate. Each day's accumulation of HDDs is simply the number of degrees

that the average daily temperature is colder than 65°F (set to zero for the day if the average temperature is 65°F or warmer). This value for each day is added up to yield an annual accumulation. Cold winters are therefore associated with large accumulations of HDDs. Cooling degree days (CDDs) are similarly defined, except that those degree days are counted when the average temperature is warmer than 65°F, requiring energy for cooling. Annual HDD accumulations have been decreasing (due to warmer winters), and CDD accumulations have been increasing (due to warmer summers) across New Mexico in recent decades. At many locations in the New Mexico annual HDD and CDD values have changed by more than 15 percent since the middle of the 20th century. Winter heating needs are diminishing in New Mexico, but the energy required for summer cooling is increasing.

## b. Current global warming is caused, in significant part, by manmade emissions of greenhouse gases.

The current generation of climate models successfully reproduces observed 20th-century temperature changes, across all continents and the world's oceans, if the models use the observed 20th-century changes in anthropogenic greenhouse gases or GHGs (principally carbon dioxide, CO<sub>2</sub>, and methane, CH<sub>4</sub>), solar brightness, and atmospheric particulates. If human-caused changes in GHGs and particulates are neglected, leaving just the natural variations due to the sun and volcanoes, then the models fail to simulate observed temperature changes. Specifically, the only way to correctly reproduce the late 20th-century warming trend is to include the effects of increasing GHG concentrations. These results provide powerful evidence that much of the warming observed in recent decades is the result of a stronger greenhouse effect, resulting from anthropogenic emissions of these gases.

#### c. Substantial warming will continue into the 21st Century.

Significant as they are, recent temperature changes are nevertheless modest compared to model-based projections for the 21st century. Given a plausible range of GHG increases in the 21st century, the models project a rise in global annual temperature of 3°F to 7°F. Recall that the total global change in the 20th century was about 1°F.

How does this range of global-average temperature increase apply to New Mexico? If we choose a mid-range GHG emissions scenario (the so-called 'A1B' scenario) and take the average of 18 global model projections developed for the 2007 report of the Intergovernmental Panel on Climate Change (IPCC), we find an increase in temperature across the state of New Mexico of more than 5°F in winter and almost 8°F in summer by the end of the century. Uncertainties in these trend estimates are associated with the rate of future GHG emissions, on unknown other climate forcings, and on model uncertainties. Projections based on different emissions scenarios reach the same warmer temperatures cited here, but decades sooner or later, depending on the rate of emissions.

#### d. Adverse impacts of the trend toward warmer climate in New Mexico.

The temperature changes listed above will have significant effects on many aspects of life in New Mexico. Some of the most profound potential changes are concerned with water, which is certainly scarce and precious here already. Projected 21st-century climate change is likely to diminish the water supply to all of southwestern North America. If the current warming trend continues, it will severely reduce snowpack across the western United States. Precipitation will fall as snow for a shorter season, the average elevation of the winter snow line will increase, and the high-elevation snowmelt will occur earlier in the spring. Climate model results shown in the

report from the state engineer's office indicate that there may be no snowpack at all south of

Santa Fe by the end of this century.

A warmer climate also leads to sharp projected decreases in soil moisture. These effects are especially pronounced during episodic drought conditions, and one important consequence of a warmer climate in the 21st century is that future droughts will have more severe impacts. Paradoxically, increased potential evaporation and warmer surface temperatures also mean that the potential for very intense precipitation events also increases. One of the general expectations for a warmer climate, borne out by recent observed trends and by model projections of future climate, is for more variability and more extreme conditions—both severe droughts and more frequent severe weather and flooding (even in the midst of long-term drought). In New Mexico we have recently experienced just such wild swings: for example, one of the driest winters in the instrumental record (2005–06) was followed by the wettest summer in 2006.

Notice that the effects on water resources discussed so far are all associated with trends in temperature, not precipitation. Unlike temperature observations, there is no clear trend in annual precipitation in the 20th-century record; instead we have experienced recurring decade-scale drought and wet spells. Tree-ring records indicate that the Southwest has alternated between multi-decadal drought and pluvial (wet spell) conditions for many centuries, as described in a recent report on historical Colorado River fluctuations issued by the National Research Council. Climate models do not agree on a clear upward or downward trend in projected summer monsoon precipitation in the 21st century.

However, the most recent set of climate projections from the IPCC shows a modest, but ominous, downward trend in total winter and spring precipitation across southwestern North America, including New Mexico. In the model simulations, rising air motions intensify near the

equator as the ocean warms, generating increasing clouds and precipitation in the tropics. A corresponding intensification of downward air motion (suppressing precipitation) occurs in subtropical latitudes, where most of the world's deserts are now located, making those arid areas even drier. If this happens, the substantial pressures on water resources associated with warming in New Mexico and other subtropical arid lands could become much worse.

The changes in climate projected for the 21st century would cause an overall decrease in flow in New Mexico's snow-fed rivers. The annual flow in the Rio Grande at the Otowi gauge, the basis for determining downstream delivery obligations prescribed in the Rio Grande Compact, is highly correlated with snowpack in southern Colorado. As snowpack decreases in a warmer climate, we should anticipate that future Otowi index flows will decrease substantially. Low annual Otowi flows (less than 750,000 acre-feet per year) have occurred during almost half of the years since the Rio Grande Compact was negotiated. It is likely that the warming trends cited above will shift most of the future Otowi flows into the low flow category. Superimposed on this trend, we should anticipate intermittent decade-scale drought and wet spells. The projected exacerbation of drought cycles by increased temperatures, in combination with a general downward trend in streamflow, presents a major challenge for water managers.

The implications for water management in all of New Mexico's major river valleys are potentially profound. Consider the water budget for the Middle Rio Grande valley downstream from Otowi. The principal inputs of water to the Middle Rio Grande are inflows from snowpack in southern Colorado and from tributary inflows. These inputs are projected to decrease in a warmer climate. The principal depletions include evaporation from open water (in the river and in reservoirs, including Elephant Butte), transpiration from plants, and withdrawals by people. All of these depletions will likely increase, due to both climate change and increasing population.

- 1 Each of the projected climate-forced trends in this budget will exacerbate water management
- 2 challenges within the Middle Rio Grande valley. But the downstream delivery obligations to
- 3 Texas imposed by the Rio Grande Compact are not changing. All of New Mexico's major snow-
- 4 fed rivers (including the Pecos, Canadian, Gila, and San Juan Rivers) will experience similar
- 5 climatic effects, leading to projections of lower flows.

2. The Impact of Climate Change on New Mexico's Water Supply and Ability to Manage Water Resources.

#### a. Manmade emissions of GHGs are causing global warming.

In the 20th Century global temperature increased by about 1°F, with much of the warming occurring after 1970. An overwhelming body of evidence, which has increased since this Water Impact Study was published in 2006, indicates that much of the increase in temperature is associated with anthropogenic GHG emissions. The GHGs are trace gases (present in small amounts in Earth's atmosphere) that actively absorb infrared radiation but are much less effective at absorbing solar radiation. Thus GHGs allow sunlight to pass through the atmosphere to the surface, but absorb and re-emit radiant heat emitted from the surface and "recycle" some of that heat back downward. Recycling of infrared radiation creates the "Greenhouse Effect" that keeps the Earth's surface significantly warmer than it would be in the absence of an atmosphere.

Although significant uncertainties remain concerning many aspects and projected impacts of current climate change, there is no longer any serious scientific debate about several fundamental results:

- 1 Earth's climate is warming on multidecadal time scales, as can be seen in the
  2 instrumental data record and the worldwide retreat of glaciers, pack ice and
  3 snowfields during the 20th Century, continuing today.
  - 2) Ice core records show that several principal atmospheric GHGs are now present in concentrations higher than at any time in the last half-million years. The abrupt rise in the concentrations of these gases since the Industrial Revolution is due without doubt to human activities. The concentrations of each of these anthropogenic greenhouse gases continues to increase rapidly; in this century it seems inevitable that CO<sub>2</sub> will reach a concentration more than double its pre-industrial value.
  - 3) The direct radiative effect of GHGs is very well understood. There is no doubt that the direct effect of increasing the atmospheric concentrations of GHGs is an increase in Earth's surface temperature.

Warming trends over the past few decades are clearly in evidence across New Mexico and the American Southwest, exceeding global average temperature trends during the same time. Since the 1960s, wintertime statewide average temperatures have increased by about 1.5°F (Water Impact Study, Fig. II-1).

It is important to keep in mind that the ongoing warming of global and regional climate is taking place in the context of shorter term weather and climate variability, as well as demographic factors that may increase our vulnerability to climate change. The American Southwest is subject to recurring severe multi-year drought episodes, which occur on average several times per century, as determined from tree ring records spanning the last thousand years (Water Impact Study, Fig. II-4). These pronounced drought episodes, which seem to be a natural

- 1 component of regional climate, are expected to continue as the climate warms. Meanwhile
- 2 human population is increasing rapidly in New Mexico, and across the southwestern U.S. and
- 3 northern Mexico, despite the limited water supply in this semiarid region.

#### b. Overview of climate trends and projections for New Mexico and the Southwest.

In the American Southwest, the impacts of climate variations on water supplies are recognizable by observing snowpack, reservoir and stream flow levels. Global climate models (GCMs) and historical trends in temperature, precipitation, and snowpack are used in combination to assess the recent and potential future effects of climate change on water resources across the Southwest and New Mexico. GCMs indicate that by the end of this century, the American Southwest, including New Mexico, can expect a significant increase in temperature, resulting in a decrease in snowpack. Precipitation projections are far less certain, as discussed already in Section 1d and considered again below. The models suggest that even moderate increases in precipitation would not offset the negative impacts to the water supply caused by increases in temperature. Projected changes in climate variability could also result in more frequent and extreme flooding.

#### i) Temperature

Climate models project that increases in temperature in the 21st Century will be greater in the Southwest than the global average, as part of a general tendency for continental interiors to warm up more than oceans or coastal regions. In the northern part of New Mexico, which is of particular importance for snow-fed river flows, the largest increases in temperatures over the past several decades have occurred in the winter months, resulting in recent annual average temperatures more than 2°F above mid-20th Century values [Water Impact Study, Figure II-1].

Recent model simulations suggest accelerated summertime warming in the future, as will be described below [Water Impact Study, Figs. II-8 and II-11].

#### ii) Snowpack

Climate models project a trend toward higher freezing altitude and a reduction in western snowpack over the coming decades as a result of rising temperatures [Water Impact Study, Fig. II-2]. The anticipated higher temperatures discussed above will have several major effects: delay in the arrival of the snow season, acceleration of spring snowmelt, and therefore a shorter snow season, leading to rapid and earlier seasonal runoff. Average temperatures have been rising in the mountainous areas of New Mexico [Water Impact Study, Fig. II-1], which supports model-based projections that snowfall will begin later and total snowfall will decrease, even if winter precipitation stays the same or increases. Snowpack has been below long-term average values for most years during the last two decades in both the Colorado River and Rio Grande Basins.

The recent observed decrease in snowpack in the Southwest has coincided with the warming trend. Climate models project that snowpack in the southern Rocky Mountains will continue to decline through the 21st Century [Water Impact Study, Figs. II-3 and II-13].

#### iii) Precipitation and streamflow

Climate models project a marked increase during the 21st Century in the ratio of rain to snow in winter precipitation. The largest percentage increases in precipitation falling as rain are likely to be along the western and southern margins of the current North American snowpack, including the Southwestern U.S. Recent model simulations also project a decline in total winter precipitation across New Mexico (Water Impact Study, Figs. II-9 and II-12), but considerable uncertainty surrounds these precipitation projections. A recent study concluded that a 7°F increase in temperature in the Colorado River Basin would require precipitation increases of 15-

- 1 20% above current averages to mitigate the decrease in flows experienced from evaporative
- 2 losses. Similarly, a study of projected streamflows in the Rio Grande basin yielded decreasing
- 3 flows associated with warmer temperatures in the mid-late 21st Century for a wide range of
- 4 assumed precipitation trends.

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#### iv) Drought

Increasing temperatures, earlier snow melt, and decreasing soil moisture lead to an increase in summertime potential evaporation, thereby decreasing recycled moisture availability and creating a cycle that perpetuates the increased intensity, frequency and duration of drought. Tree ring-based reconstructions of western droughts over the last millennium show a correlation between warm temperatures, drought, and lower streamflow, indicating that long-term warming trends could lead to extreme aridity across the western United States. A reconstruction dating back to 1512 indicates that long-term annual flow in the Colorado River was likely 10% less than the average annual flows measured from 1906 to 2000. Another reconstructed precipitation history derived from old trees in northern New Mexico shows that recent decades have been relatively wet compared to the long term climatic average [Water Impact Study, Fig. II-4]. The 1950s drought, the most severe drought in New Mexico in the 20<sup>th</sup> Century instrumental record, shows up as a severe episode in this reconstruction but is by no means the worst drought in the past 1000 years. This long record, like other reconstructions from different parts of the Southwest, shows that episodic droughts lasting a decade or more have been a recurring feature of Southwest climate for many centuries. These droughts are currently not predictable, but New Mexicans should assume that severe droughts (like the 1950s, or worse) will continue to occur in the future.

#### v) Flood events

Warming trends will result in shifts and changes in the magnitude of runoff peaks that depend on overall precipitation. As discussed above, warming at high elevations will decrease winter snowfall and snowpack, increase winter rainfall, and accelerate spring snowmelt, causing probable increases in winter runoff and decreases in spring and summer streamflow. Increases in summer surface temperatures will likely result in increased atmospheric instability and deep convection (i.e. more intense thunderstorms), and a more vigorous hydrologic cycle, resulting in a climate conducive to more intense (but possibly less frequent) storms, thereby leading to an increase in flood events. Peak flows could increase significantly during the part of the year that now precedes the annual spring snowmelt, and corresponding flood events could be earlier and more extreme.

#### c. Climate projections for New Mexico using a regional climate model.

Any realistic scenario of GHG concentrations in the 21<sup>st</sup> Century calls for an increase, as is clearly observed to date. The effect of increasing GHG concentrations is to warm the climate. The principal difference in the climate change projections is in the rate and timing of warmer temperatures, not in whether warming occurs at all. Scenarios with higher GHG emissions levels generate faster warming trends and more severe climate changes at any particular future time (still subject to uncertainties in short-term variability as discussed in Section 1c). Therefore the selection of an emissions scenario mostly affects the date at which a certain level of warming (or snowpack decline, etc.) is reached.

The most consistent climate change in New Mexico forced by increasing GHGs in global models is a strong temperature trend toward warmer conditions, not a systematic change in total precipitation one way or another. As shown in Fig. II-11b of the Water Impact Study, significant

- 1 warming occurs year-round in association with GHG increases, with the greatest warming in the
- 2 summer season. One consequence of pronounced summer temperature increase is an increase in
- 3 both the magnitude and length of extreme heat waves. Water resources in New Mexico would
- 4 be greatly affected by the warming trend, even in the absence of significant precipitation change.
- 5 The magnitude of winter and spring warming has profound consequences for snowpack
- 6 throughout the interior of western North America. Fig. II-13 of the Water Impact Study shows
- 7 the change in snowpack (expressed in mm H<sub>2</sub>O content, commonly referred to as "Snow Water
- 8 Equivalent" or SWE in observed data) for:
- 9 (a) New Mexico, March 1 average,
- 10 (b) New Mexico, April 1 average, and
- 11 (c) eastern Utah/western Colorado, April 1 average.
- 12 The current average date of maximum snowpack in southern New Mexico is around March 1,
- while snowpack in northern New Mexico and southern Colorado typically reaches its maximum
- around April 1. In the model simulation considered for this study, the late 21st Century climate
- under a high-emissions scenario includes no sustained snowpack south of Santa Fe and the
- 16 Sangre de Cristo range. Snowpack remains in far northern New Mexico and southern Colorado
- 17 (the headwaters region of the Rio Grande), but is greatly reduced in mass by the end of this
- 18 century. The April 1 climate change in Fig. II-13c of the Water Impact Study shows reductions
- in April 1 SWE of 50-200 mm H<sub>2</sub>O, compared to an average in the 1961-1985 simulation of
- 20 100-300 mm H<sub>2</sub>O across the San Juan Mountains, i.e. a decrease in water mass between one-
- 21 third and one-half. Total runoff into rivers and reservoirs fed by snowmelt is therefore likely to
- be reduced, with the greatest decreases in the spring season.

Soil moisture changes are most pronounced in the spring (March-May) season, shown in Fig. II-14 of the Water Impact Study. The largest changes are seen in northwest New Mexico, where the upper layer soil moisture content decreases by about 20% relative to a simulation of current climate using the same model. This change is associated with the decrease in snowpack in the springtime. Soil moisture in the summer season also decreases but less in absolute terms, because soils are dry then even in the current climate. Evaporation from the surface decreases in the summer season (June-August) in one simulation, shown in Fig. II-15 of the Water Impact Study, representing a reduction of 25% or more relative to current evapotranspiration rates simulated by the model. This is the result of drier soils and (in this simulation) less summer rainfall, and produces a positive feedback on the temperature trend in summer by reducing the surface cooling effect of evaporation.

There are several points worth noting concerning the evaporation changes simulated by the model. First, reduced summer evapotranspiration simulated by the model is associated with drier surface conditions. Where the surface is not dry (such as the water surface of a reservoir), evaporation rates are certain to *increase*, not decrease, under the 21st Century climatic conditions simulated by this model. Thus depletion of water resources by evaporation from reservoirs would increase. Second, the change in average climate simulated here would greatly increase New Mexico's vulnerability to recurring drought episodes. Drought conditions would exacerbate the surface dryness that the regional model simulates as a mean condition in the late 21st Century. Warmer temperatures, more extreme heat waves, and a drier surface would make drought episodes more extreme in the changed climate.

The simulated regional climate changes, if realized, would have profound consequences for the hydrologic cycle across New Mexico. In the cold season (winter and spring), snowpack

- 1 would be reduced even if total precipitation stays the same or increases somewhat -- and model
- 2 projections include the possibility of a reduction in winter precipitation. In the warm season,
- 3 warmer temperature and drier land surface conditions would raise evaporation rates off open
- 4 water surfaces and increase vulnerability to drought cycles. These statements remain valid
- 5 despite continuing uncertainty concerning long-term climatic trends in total precipitation rates in
- 6 both winter and (especially) summer.

## 3. Climate Variability and Projected Change in the Western United States: Regional Downscaling and Drought Statistics.

In the Drought Study, the 21<sup>st</sup> Century climate change projected by a large ensemble average of global coupled models, forced by the A1B GHG scenario, was "downscaled" to climate divisions across the western United States. A simple empirical technique was employed to do this, involving model projected linear trends in temperature or precipitation superimposed onto a repetition of observed 20<sup>th</sup> Century interannual variability. This procedure allows the projected trends to be assessed in terms of historical climate variability. The linear trend assumption appears to provide a very close approximation to the ensemble-average trends. The imposition of repeated interannual variability is probably conservative, given the projections of increased variability in a warmer climate as discussed in Section 1d. Projected warming trends in some areas of the western U.S. extend beyond the 20th Century historical range of variability of seasonal averages, especially in summer, whereas precipitation trends are relatively smaller, remaining within the historical range of interannual variability.

These temperature and precipitation projections were used to generate values of the monthly Palmer Drought Severity Index (PDSI) across the western U.S. through the 21st Century, using the 20th Century as a baseline. The PDSI is a commonly used operational metric designed to describe drought in terms of the local surface water balance. These results suggest

- 1 progressively increasing severity, duration, and frequency of drought during this century. The
- 2 general trends in temperature and precipitation shown in the scenario presented in the Drought
- 3 Study have been discussed extensively already in this testimony. By placing these trends into the
- 4 context of observed interannual and decadal variability, the following conclusions can be drawn:
- 5 The summer temperature trend stands out from interannual variability exhibited in
- 6 the 20<sup>th</sup> Century record, principally because interannual variability is much smaller in summer
- 7 than in winter. By the late 21st Century in this scenario, summer temperature every year exceeds
- 8 any summer temperatures ever recorded in the 20<sup>th</sup> Century.
- 9 Palmer Drought Severity Index scenarios are derived as a proxy for surface water
- 10 budget changes in the 21st Century. This study described sharp increases in the severity and
- duration of 21st Century drought (relative to 20th Century drought statistics), and the spatial
- scale of future droughts expands to cover much of the West. Furthermore, 21st century droughts
- 13 are driven by temperature to a greater degree than historical droughts. Recovery from
- 14 historically precipitation-driven drought, repeated in these scenarios in the 21st Century, is
- inhibited by the increased evaporation implied by warmer temperature in the climate change
- scenario developed here. As a result, the recovery from multi-year precipitation deficits, such as
- 17 those that have occurred intermittently during the past millennium (and are likely to reoccur in
- some form in the current century) will be much more difficult in the warmer projected climate.
  - 4. Predicting future threats to the long-term survival of Gila trout using a high-resolution simulation of climate change.
- The regional climate model used in the Gila Trout Study projects a 20% decrease in
- 23 summer precipitation, a nearly 2°C increase in summertime average air temperature, and a
- pronounced increase in the number of days above 32°C and 37°C, by the middle of the 21st
- century in the small region inhabited by Gila trout, a cold-water salmonid fish. The combination

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1 of precipitation and temperature change in this simulation would have a profound long-term

2 impact on the Gila trout. The increase in average summertime temperatures and the number of

days above 37°C will increase thermal loading in the water, limiting the movement of the Gila

Trout to lower altitudes during the summer season. Gila trout populations are currently limited

5 to 1,660 m and 2,810 m in elevation depending on the drainage they inhabit. Calculations

indicate that a 2°C change in average seasonal air temperatures would cause an elevational range

shift of between 250 m and 300 m. This could represent a 70% loss in suitable habitat for

existing trout streams in July based on changes in elevation.

The control simulation for the current climate accurately predicted that the lowest elevation for Gila trout would be 1,686 m based on a thermal tolerance of 25°C, and predicted the average low elevation based on mean July surface air temperature of 22°C. This corresponds well with other published reports for cold water Salmonids and laboratory studies. Gila trout habitat is located at a lower latitude than many other trout species so Gila trout may be better acclimated to slightly warmer temperatures, as shown by laboratory studies on races of cutthroat trout that inhabit wide geographic regions. These results are qualitatively similar to other predictions that global warming will reduce suitable habitat for cold water species.

Decreases in summer precipitation, which are less pronounced and less certain than the temperature changes, would reduce stream flow. In addition, base flow will decrease as a result of diminished snow pack and earlier snowmelt runoff associated with warmer winter temperatures. If the headwater streams that currently act as warm season refugia for the trout become greatly reduced or ephemeral, then the Gila trout would become stressed or suffer higher mortality as they are limited to sub-optimal habitat in warmer waters downstream.

A decrease in suitable Gila trout habitat as a result of the projected scenario would lead to further declines in populations and increased risk to environmental and demographic stochastic events. For example, decreased precipitation and a longer warmer season would increase the fire potential, both in frequency and severity. Thus, even if local climate change does not directly cause of the demise of Gila trout, indirect effects and stochastic events could be equally important.

All climate change projections are dependent on the particular model and GHG forcing scenario chosen, and do not account for climate forcings other than anthropogenic GHGs and aerosols, so any projection is subject to considerable quantitative uncertainty. However the changes described in the Gila Trout Study are qualitatively similar to many other large-scale simulations of climate change at high elevation in the interior of North America.

#### 5. Synthesis and Discussion

On a global scale, the accumulation of diverse evidence for human-caused global warming is so substantial that the IPCC considered such evidence to be 'unequivocal' in its 2007 report. As the various statements from American scientific societies affirm, there is no serious scientific debate about the following points: (1) the Earth is warming on climatic time scales; (2) atmospheric concentrations of significant greenhouse gases are increasing rapidly as the result of human-caused emissions; (3) the direct radiative effect of increasing greenhouse gas concentrations will cause the surface of Earth to get warmer.

Upward temperature trends are already clearly observed in New Mexico. Projections of future climate in the 21st Century, based on a plausible 'mid-range' greenhouse gas emissions scenario, include very significant trends toward conditions that would be much warmer than any instrumental observations made in the 20th Century. There is good agreement among different

1 climate models in support of the projected warming, and these models have demonstrated

2 considerable skill in reproducing broad-scale multi-decadal climate trends during the 20th

Century. In a semiarid climate such as New Mexico's, such warming would shift the surface

water balance toward much drier conditions, including diminished streamflows.

It is important to re-emphasize the strength and diversity of the scientific evidence for the foregoing conclusions, especially in view of recent public controversy over hacked emails and isolated errors in the IPCC reports. The controversy is dismaying and has clearly indicated the need for improvements in the vetting process associated with IPCC publications. Public perceptions of climate science have been damaged, which clearly was the purpose of publicizing stolen emails and isolated errors. From a scientific perspective, however, there is nothing in the recent controversy, stolen emails, or isolated errors that changes the wealth of evidence, both observational and theoretical, supporting the body of results that I have summarized in the body of my testimony. None of the professional societies referenced earlier have retracted or retreated from their statements; indeed the Geological Society of America's statement was formulated and issued after the controversy.

It is equally important to re-emphasize that there are significant quantitative uncertainties regarding the magnitude and rate of future climate change, both globally and in New Mexico. Furthermore, it is unrealistic to think that climate science will evolve to the point at which climate projections can be treated like daily weather forecasts (which are quite accurate almost every day). The likely impacts of climate change in this century are profound, but policymakers will always need to make climate-related decisions using projections that contain broad uncertainties.

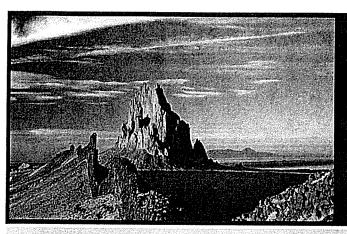
Waiting to set policy until climate projections become certain is itself a policy decision, because the climate will change before the wait is over. Meanwhile, the time scale for the world's oceans to redistribute heat is a century or more, which means that today's enhanced greenhouse effect will affect the climate for many decades to come. Climate model studies show that the climate would continue to warm throughout the 21st Century as the result of 20th Century greenhouse gas emissions, even if the current greenhouse gas concentration could be immediately stabilized (which we know is impossible). By failing to reduce greenhouse gas emissions now, therefore, the models indicate that we are making a commitment to long-term warming for several generations to come.

As implied above, climate change projections are not like weather forecasts; instead the studies cited here are generally based on a particular 'scenario' that represents one among many possible climate futures. It should be understood that the impacts of increasing GHGs are very likely to increase as greenhouse gas concentrations increase; lower emissions would result in a reduced rate of increase in global GHG concentrations, which would reduce the magnitude and rate of change of climate. I have pointed out several times in this testimony the relationship between global emissions scenarios and rates of change of climate. Climate change will occur faster for higher GHG emissions rates. In considering uncertainties in our climate future, it is important to keep in mind that the A1B radiative forcing scenario that I have often used for projecting New Mexico climate was considered a 'mid-range' scenario when it was developed in the 1990s. In fact this scenario seriously underestimates the global emissions that have occurred in the past 15 years, and global emissions show no sign at present of the eventual abatement of emissions assumed in the A1B scenario.

It is my professional opinion that the climate of New Mexico is now changing, and will
continue to change during the 21st Century, toward the conditions I have described in the studies
cited in this testimony. However I cannot say with certainty how quickly these changes will
occur, or what shorter-term fluctuations will take place along the way. The EIB needs to
understand that the trends I have described could occur more slowly, or more rapidly, depending
on the limitations in our current ability to simulate and predict the global climate system, on
other climate forcings that are inadequately represented, and on the greenhouse gas emissions
path that we choose to take.

As a climate scientist I feel strongly that I should limit my comments to the science, and leave specific policy prescriptions to others. However it is my hope and recommendation that the EIB in its deliberation take a long-term view of the projected costs and benefits of addressing climate change. Much of the political debate over climate change, like so much policy discussion, focuses on short-term costs and benefits, and short-term perceptions of "winners" or "losers". In my opinion we typically do a poor job of looking beyond such short-term considerations. But the impacts of climate change that I have described would involve huge generational inequities. Present-day greenhouse gas emissions, which support the high quality of life we enjoy today, will affect our children and grandchildren much more than ourselves. Our society can no longer pretend to be ignorant of the potential long-term impacts of human-caused climate change. We should assume a responsibility to future generations to address this issue honestly and seriously.

David S. Gutzler, PhD



# New Mexico EARTH MATTERS

**Summer 2007** 

#### CLIMATE CHANGE AND WATER RESOURCES IN NEW MEXICO

In the Summer 2004 issue of Earth Matters, we featured an article on "New Mexico's Changing Climate," by David Gutzler. That article provided an introduction to the factors that determine climate and climate variability in New Mexico. In this follow-up article, Dr. Gutzler provides an update on what we've learned in the past three years and explores some model-based predictions of 21stcentury climate change in New Mexico, with special emphasis on how such change will likely affect water resources. He draws upon some recently published results, including the new assessment by the Intergovernmental Panel on Climate Change, and a report on the impacts of climate

change on New Mexico's water resources issued by the Office of the State Engineer. Both are accessible online; see Additional Reading at the end of this article.

New Mexico's climate is now warmer than at any time during the past century, the period for which we have instrumental temperature records. The time series of statewide average temperature (top of page 2) for both the cold half of the year (October through March) and the warm half (April through September) suggests some cooling during the initial decades of the 20<sup>th</sup> century. The 1950s drought years were characterized by higher temperatures in the warm season but not in the cold season. Rapid warming has occurred year-round since the 1960s and continues today-with an increase of roughly 2°F in the cold season and nearly 3°F in the warm season since that time. These warming trends are more than twice the annual global average trend, which was about 1°F over the entire 20th century. This is consis-



Sierra Blanca in south-central New Mexico. Climate models suggest that there may be no snowpack at all in New Mexico south of Santa Fe by the end of this century. Photo © Laurence Parent.

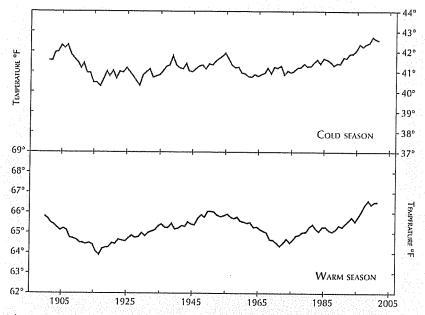
tent with the expectation that continental temperature should be more variable than oceanic temperature; oceans cover more than 70 percent of our planet. Think about the difference between a hot, sandy beach and a nearby body of water on a sunny summer afternoon.

The ongoing warming trend in New Mexico is quite significant already. Utility companies measure annual heating requirements using "heating degree days" (HDDs), a measure that relates each day's temperature to the demand for energy for heating. These values are used by state regulators in setting gas rates, so the average annual HDD accumulation is an important economic index of climate. Each day's accumulation of HDDs is simply the number of degrees that the average daily temperature is colder than 65°F (set to zero for the day if the average temperature is 65°F or warmer). This value for each day is added up to yield an annual accumulation. Cold winters are therefore associated

with large accumulations of HDDs. Cooling degree days (CDDs) are similarly defined, except that those degree days are counted when the average temperature is warmer than 65°F, requiring energy for cooling. Annual HDD accumulations have been decreasing (due to warmer winters), and CDD accumulations have been increasing (due to warmer summers) across New Mexico in recent decades, and by a lot. At the sites plotted on the next page, which are quite representative of other locations in the state, annual HDD and CDD values have changed by more than 15 percent since the middle of the 20th century.

Winter heating needs are diminishing in New Mexico, but the energy required for summer cooling is going up fast.

Significant as they are, recent temperature changes are still modest compared to model-based predictions for the 21st century. The current generation of climate models successfully reproduces observed 20<sup>th</sup>-century temperature changes, across all continents and the world's oceans, if the models use the observed 20th-century changes in greenhouse gases (principally carbon dioxide, CO2, and methane, CH4), solar brightness, and atmospheric particulates. If human-caused changes in greenhouse gases and particulates are neglected, leaving just the natural variations due to the sun and volcanoes, then the models fail to simulate observed temperature changes. Specifically, the only way to correctly reproduce the late 20th-century warming trend is to include the effects of increasing greenhouse gas concentrations. Given a plausible range of greenhouse gas increases



20<sup>th</sup>-century time series of observed New Mexico statewide temperature, with the year split into a 6-month "cold season" (October-March, blue curve) and a 6-month "warm season" (April-September, red curve). The time series have been smoothed to emphasize decadal variability. Data were obtained from the Western Regional Climate Center, Reno, Nevada.

in the 21st century, these same models predict a global rise in annual temperature of 3°F to 7°F. Recall that the total global change in the 20th century was about 1°F.

How does this range of global-average temperature increase apply to New Mexico? If we choose a mid-range greenhouse gas emissions scenario and take the average of 18 global model predictions, then the models predict an increase in temperature across the state of New Mexico of more than 5°F in winter and about 8°F in summer by the end of the century! The precise rate of warming depends on future greenhouse gas emissions, and there's no way to know what choices we will make regarding such emissions. Predictions based on different scenarios reach the same warmer temperatures cited here, but decades sooner or later, depending on the rate of emissions.

The evidence for greenhouse gas-forced warming is extremely compelling. That's why the climate research community almost unanimously now considers some amount of global warming in the 21st century to be inevitable. The scientific debate on whether greenhouse gas-forced global warming is real, and will continue, is effectively over. Current scientific research on global warming is now focused on how much and how fast the climate will warm.

#### **Hydrologic Cycle Changes**

The temperature changes listed above will have significant effects on many aspects

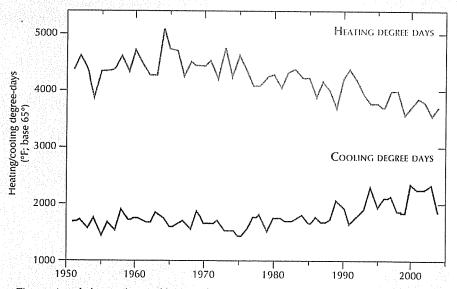
of life in New Mexico. Some of the most profound potential changes are concerned with water, which is certainly scarce and precious here already. Predicted 21st-century climate change is likely to diminish the water supply to the entire western half of the United States. If the current warming trend continues, it will severely reduce snowpack across western North America. Precipitation will fall as snow for a shorter season, the average elevation of the winter snow line will increase, and the remnants of high-elevation snowpack will melt earlier

in the spring. Climate model results shown in the report from the state engineer's office (see *Additional Reading*) indicate that there may be no snowpack at all south of Santa Fe by the end of this century.

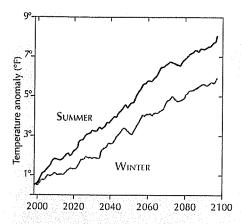
A warmer climate also leads to an increase in evaporation during spring and summer, and to sharp predicted decreases in soil moisture. These effects are especially pronounced during episodic drought conditions, and one important consequence of a warmer climate in the 21st century is that future droughts will have more severe impacts.

Paradoxically, increased evaporation and warmer surface temperatures also mean that the potential for very intense precipitation events also increases. One of the general expectations for a warmer climate, borne out by model predictions, is for more variability and more extreme conditions—both severe droughts and more frequent severe weather and flooding (even in the midst of long-term drought). In New Mexico we have recently experienced just such wild swings: one of the driest winters in the instrumental record (2005–06) was followed by the wettest summer last year.

Notice that the effects on water resources discussed so far are all associated with trends in temperature, not precipitation. Unlike temperature observations, there is no clear trend in annual precipitation in the 20<sup>th</sup>-century record; instead we have experienced recurring drought and wet spells. Tree-ring records indicate that the Southwest has alternated between multidecadal drought and pluvial (wet spell)



Time series of observed annual heating degree days at Fort Bayard, east of Silver City, New Mexico (blue curve, representing the cold season) and cooling degree days at Las Cruces (red curve, representing the warm season). Other locations in New Mexico show changes over the past several decades similar to these examples.



21st-century time series of predicted New Mexico statewide temperature variations for summer (red curve) and winter (blue curve), derived from an average of 18 global climate model simulations forced by the Intergovernmental Panel on Climate Change (scenario A1B) to describe future greenhouse gas concentrations. The time series have been smoothed to emphasize decadal variability. Values on the y-axis represent the temperature change relative to each model's simulated climatology for the late 20th century (so that the simulated 1971-2000 New Mexico average temperature is assigned a value of 0 for each model; this emphasizes temperature changes relative to the present). This plot is adapted from the climate change report issued by the New Mexico Office of the State Engineer in 2006.

conditions for many centuries, as described in a recent report on historical Colorado River fluctuations issued by the National Research Council. Climate models also show no clear trend in predicted summer monsoon precipitation in the 21st century.

However, the most recent set of climate predictions from the Intergovernmental Panel on Climate Change (IPCC) shows an ominous downward trend in total winter precipitation across southwestern North America, including New Mexico. In the model simulations, rising air motions intensify near the equator as the ocean warms, generating increasing clouds and precipitation in the tropics. A corresponding intensification of downward air motion (suppressing precipitation) occurs in subtropical latitudes, where most of the world's deserts are now located, making those arid areas even drier. If this happens, the substantial pressures on water resources associated with warming in New Mexico and other subtropical arid lands could become catastrophic. A 2007 paper in Science magazine by Seager et al. uses the term "megadrought" to describe the 21st-century climate across southwestern North America simulated in the IPCC predictions.

#### Implications For Water Management

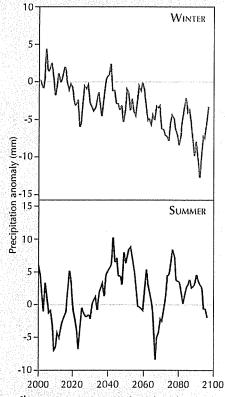
Climate change is hardly the only important factor in the development of sustainable water resources in New Mexico. State water managers must plan for increasing population, economic development, ongoing depletion of ground water reservoirs, and the desire to maintain a healthy riparian environment, as they administer water rights within the established legal framework. The state of New Mexico has an overarching legal obligation to satisfy annual downstream delivery requirements to the neighboring state into which each of our major rivers flows. The state's consumptive use of water from the Rio Grande, for example, is limited by an agreement called the Rio Grande Compact. New Mexico's annual delivery obligation to Texas depends on the stream flow that passes the Otowi gage below Los Alamos. During years with low flows both the downstream delivery requirement and New Mexico's allowed depletion are reduced, so the pain of drought is shared between New Mexico and Texas. The extra water flowing past Otowi during high flow years (anything more than 1,250,000 acre-feet per year) all goes to Texas.

The changes in climate predicted for the 21st century would cause an overall decrease in flow in New Mexico's snow-fed rivers. The annual flow at Otowi is highly correlated with snowpack in southern Colorado. As snowpack decreases in a warmer climate, we should anticipate that future Otowi index flows will decrease substantially. Low annual Otowi flows (less than 750,000 acre-feet per year) have occurred during almost half of the years since the Rio Grande Compact was negotiated. It is likely that the warming trends cited above will shift most of the future Otowi flows into the low flow category, with a significant overall downward trend during the 21st century. Superimposed on this trend, we should anticipate intermittent severe drought episodes, during which flows are even lower.

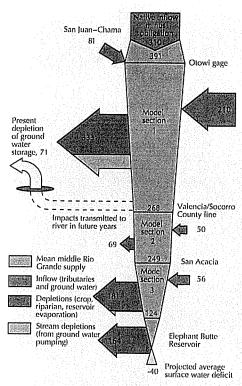
The implications for water management in all of New Mexico's major river valleys are potentially profound. Consider the water budget for the Middle Rio Grande valley downstream from Otowi. The principal inputs of water to the Middle Rio Grande are inflows from snowpack in southern Colorado and from tributary inflows. These inputs are predicted to decrease in a warmer climate. The principal depletions include evaporation from

open water (in the river and in reservoirs, including Elephant Butte), transpiration from plants, and withdrawals by people. All of these depletions will likely increase, especially considering the new extraction and treatment plant now under construction by the city of Albuquerque. But the downstream delivery obligations to Texas are not changing. So each of the predicted climate-forced trends in this budget will exacerbate water management challenges within the Middle Rio Grande valley.

Although this discussion has focused on the Rio Grande, all of New Mexico's major snow-fed rivers (including the Pecos, Canadian, Gila, and San Juan Rivers) will experience similar climatic effects, leading to predictions of lower flows. Will we have the foresight to plan for shortages of water during severe droughts and lower river flows in the years to come?



21st-century time series of predicted New Mexico precipitation variations for winter (blue curve, top) and summer (red curve, bottom), derived from an average of 18 global climate model simulations forced by the Intergovernmental Panel on Climate Change (scenario A1B) to describe future greenhouse gas concentrations. Values on the y-axis represent differences from current climatological values. The time series have been smoothed to emphasize decadal variability. Note the difference between winter precipitation, which exhibits a pronounced downward trend, and summer precipitation, which varies between wet spells and droughts but does not show a clear trend.



Water budget for the Middle Rio Grande; numbers are thousands of acre-feet per year. Climate change is expected to increase depletions (the red arrows) and decrease inflows (the green arrows), resulting in lower flow in the river. From Hathaway and McClune in Water Resources of the Middle Rio Grande, published in 2007 by the New Mexico Bureau of Geology and Mineral Resources.

#### Hard Choices for New Mexicans

How will we respond to these challenges? At present the evidence overwhelmingly indicates that warming trends will continue, regardless of any actions taken to reduce greenhouse gas emissions. No one is seriously suggesting that we can stop greenhouse gas emissions altogether. Even if we did, warming would continue, because the climate system does not respond immediately to greenhouse gas emissions. The global oceans take up extra carbon dioxide and heat energy out of the atmosphere very slowly, redistributing gases and warmth throughout the deep ocean for many years. Furthermore, it takes time for surface changes to occur, such as the melting of ice sheets. This means that the carbon dioxide emissions we generate today will have effects for decades to come, creating what we call a "current commitment" to future climate change.

We need to think seriously about adapting to the climate changes that are already occurring, based on the rational assumption that a warming trend of uncertain magnitude will continue into the future. Many facets of our lives will be affected by climate change. The State of New Mexico Agency Technical Work Group in 2005 published a report on potential effects of climate change on New Mexico. This report examined a wide spectrum of impacts in New Mexico.

As an example, how will we manage the water budget shown at left? River flows in New Mexico are already fully allocated, and inflows will likely decrease. As a democratic society, we must be prepared to make difficult choices based on broad input from the entire community. Maintaining sustainable water resources represents a particularly large and contentious challenge. Who won't get the water they desire?

Most of the scenarios used by climatologists for 21st-century predictions assume that per capita greenhouse gas emissions will decrease over the coming decades, but we don't really know how this will be achieved. Presumably some mix of conservation, increased efficiency, alternative energy development, and carbon sequestration will move us toward a lower-emissions future. Accomplishing this while maintaining the energy supplies required for a healthy economy will be a huge challenge. Several western governors (including ours) have promoted a regional effort to decrease greenhouse gas emissions. On the national level, however, government policy to date can only be characterized as inaction based on willful disregard of our best science.

I'm now 51 years old. Unless a nasty surprise occurs, climate change may not

#### **Additional Reading**

The Intergovernmental Panel on Climate Change has three working groups that are each publishing separate reports in 2007. Summaries of each report are available online at http://www.ipcc.ch

The State of New Mexico has produced the following reports:

Potential effects of climate change on New Mexico. State of New Mexico Agency Technical Work Group, 2005. Available at http://www.nmenv.state. nm.us/aqb/cc/Potential\_Effects\_ Climate\_Change\_NM.pdf

The impact of climate change on New Mexico's water supply and ability to manage water resources. Issued by the New Mexico Office of the State Engineer/ Interstate Stream Commission in 2006. Available at http://www.nmdrought.state.nm.us/ClimateChangeImpact/completeREPORTfinal.pdf

dramatically affect my quality of life. But global warming involves huge generational inequities: I burn fossil fuels today, as I have for decades, leaving our children and grandchildren to cope with the aftereffects. Our society can no longer pretend to be ignorant of the potential impacts of human-caused climate change. We have demonstrated a powerful ability to confront and overcome tremendous challenges in the past, when we decide to act. Effectively addressing climate change is, without doubt, a daunting task. Nevertheless, we should assume a responsibility to future generations to address this issue honestly and seriously.

> —David S. Gutzler Dept. of Earth & Planetary Sciences University of New Mexico gutzler@unm.edu

David Gutzler is a professor of meteorology and climatology at the University of New Mexico in Albuquerque. His research is focused on interannual and decadal variability and predictability of climate in the Southwest.

Each issue of Earth Matters features an invited article on a subject of interest to New Mexicans. These articles represent the author's informed opinion on important geoscience issues in New Mexico and do not necessarily represent the views of the New Mexico Bureau of Geology and Mineral Resources, a non-regulatory agency.

-Ed.

See also:

Seager et al., 2007, Model projections of an imminent transition to a more arid climate in southwestern North America. *Science*, 25 May 2007. Vol. 316. no. 5828, pp. 1181–1184.

Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability. National Research Council, Water Science and Technology Board, National Academies Press, 2007. Available in print or online at http://books.nap.edu/catalog.php?record\_id=11857#top

Water Resources of the Middle Rio Grande, edited by L. Greer Price, Peggy S. Johnson, and Douglas Bland, 2007 Decision-Makers Field Guide, published by the New Mexico Bureau of Geology and Mineral Resources. Available at http://geoinfo.nmt.edu/publications /decisionmakers/home.html

#### BUREAU NEWS

#### Decision-Makers Field Conference 2007

In May 2007 the bureau sponsored its fifth Decision-Makers Field Conference. This year's topic was water resources of the Middle Rio Grande from San Acacia to Elephant Butte. Over 50 people attended, including 17 legislators. The two-day conference focused on issues of statewide importance, including surface water management and infrastructure, the physical and biological framework, and opportunities for long-term bosque preservation. Stops included San Acacia Dam and Elephant Butte Reservoir. The guidebook produced in association with the 2007 conference (see back cover of this issue) has been enormously popular and is available to the public, for purchase through our Publication Sales Office, or as a free download from our Web site (www.geoinfo. nmt.edu/publications).

#### Rockin' Around New Mexico

This year's Rockin' Around New Mexico was held in Los Alamos and focused on earthquakes and volcanoes. Thirty-five teachers attended the 3-day workshop in July. Topics included an overview of volcanoes in New Mexico, geologic time, igneous rocks, geothermal resources, and seismology and earthquake safety. Field trip destinations in the Jemez Mountains included the Valles caldera and Soda Dam. Funding for much of this year's workshop was provided by the New Mexico Department of Homeland Security and Emergency Management through a federal grant for training. About a dozen staff from New Mexico Tech and Los Alamos National Laboratory were involved in this year's workshop. For information on next year's workshop, contact Susie Welch (susie@nmt.edu).

#### **Mineral Symposium**

The 28th annual Mineral Symposium will be held on the campus of New Mexico Tech on November 10–11, 2007. Sponsored by the Mineral Museum on the campus of New Mexico Tech, this year's symposium will include a day and a half of short papers. Featured keynote speaker is Dr. John Rakovan from the Department of Geology at Miami University in Oxford, Ohio. For more information or to register, call 505-835-5490.

#### **Earth Science Week**

Earth Science Week, a national event organized by the American Geological Institute (AGI) since 1998, will run October 14–20,

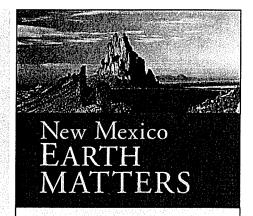
2007. This year's theme is "The Pulse of Earth Science." The New Mexico Bureau of Geology and Mineral Resources will be planning a number of local events, including an afternoon of earth science activities at the New Mexico Museum of Natural History and Science in Albuquerque on October 20 from 12 noon to 4 p.m. We will also be mailing Earth Science Week planning kits to teachers around the state who have participated in bureau programs. For more information on local activities, contact Susie Welch (susie@nmt.edu), or visit the official AGI-sponsored Web site at http://www.earthsciweek.org/

#### Sevilleta Open House

On Saturday, October 13, 2007, the Sevilleta National Wildlife Refuge will host their annual open house. A number of scientists, including the bureau's Dr. David Love and Dr. Richard Chamberlin, will lead field trips on Saturday. Most of the refuge is closed to the public throughout the year, and this event presents a unique opportunity to see areas that are otherwise not accessible. The New Mexico Bureau of Geology and Mineral Resources will join many other exhibitors at the refuge Visitor Center from 10 a.m. to 3 p.m. on that day. The Sevilleta National Wildlife Refuge Visitor Center is located approximately 19 miles north of Socorro off I-25 at Exit 169; go west 34 of a mile from the exit to reach the headquarters and Visitor Center. For more information, visit their Web site at www.fws.gov/southwest/REFUGES /newmex/sevilleta/

#### **New Hires**

We welcome two new staff persons to the bureau this summer. Talon Newton, hydrogeologist, will complete his Ph.D. in environmental engineering from Queens University in Belfast in 2008. Trevor Kludt, hydrogeologic lab associate, holds a Ph.D. in archaeology from the University of New Mexico. Both will be working in the Sacramento Mountains with the bureau's Aquifer Mapping Project, funded by the Otero County Soil and Water Conservation District with funds allocated by the state legislature. This multi-year project, which began in 2005, will use geologic and hydrologic data to characterize the local and regional aquifer systems, define limits of the aquifers, and identify geologic controls on recharge and movement of ground water.



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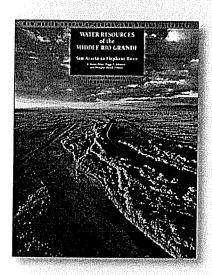
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Cover photo of Ship Rock, New Mexico
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#### **PUBLICATIONS**

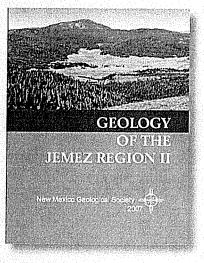


Water Resources of the Middle Rio Grande,

L. Greer Price, Peggy S. Johnson, and Douglas Bland, editors, 2007. ISBN 978-1-883905-24-8. \$15 plus shipping and handling and taxes, where applicable.

The timely collection of 25 articles provides a broad overview of issues related to water resources on the Middle Rio Grande. Written for the general public, it addresses critical issues of statewide importance,

including surface water management and infrastructure, the physical and biological framework, legal challenges that lie ahead, and opportunities for long-term bosque preservation. Produced in conjunction with the fifth Decision-Makers Field Conference held in Socorro, New Mexico in May 2007, this volume will be an important reference for anyone interested in water in New Mexico. Full color.

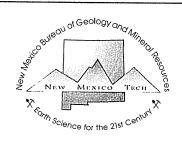


Geology of the Jemez Region II, Barry S. Kues, Shari A. Kelley, and Virgil W. Lueth, editors, 2007. ISBN 978-1-58546-094-6 \$55 plus shipping and handling and taxes, where applicable. Available September 24.

The Jemez Mountains include one of the country's best records of volcanic processes over the past 15 million years. The range is dominated by the Valles caldera, a 1.25-million-year-old, 22-kilometer-wide

structure that is the world's type example of a resurgent caldera. The caldera and associated features are now largely protected by the Valles Caldera National Preserve. This 2007 New Mexico Geological Society Guidebook, produced for the 58th annual field conference, presents new studies on the geology of this region. Four comprehensive, profusely illustrated road logs describe the geology of the area, and more than 35 research papers document latest discoveries and new, detailed geologic mapping, including structure and stratigraphy of the Española Basin, hydrology and environmental geology, Pleistocene caldera lakes, and other aspects of the Jemez region. With sixteen color plates.

For more information about these and other bureau publications: Visit our Web site at geoinfo.nmt.edu; write or visit our Publications Sales Office on the campus of New Mexico Tech, 801 Leroy Place, Socorro, New Mexico 87801; call (505) 835-5490, or e-mail us at pubsofc@gis.nmt.edu. Payment (check or money order payable to NMBGMR) must be enclosed with mailed orders. Telephone orders may be paid with VISA, American Express, or MasterCard. Additional charges for shipping and gross receipts tax (New Mexico residents) are not reflected.



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# THE IMPACT OF CLIMATE CHANGE ON NEW MEXICO'S WATER SUPPLY AND ABILITY TO MANAGE WATER RESOURCES

New Mexico Office of the State Engineer/Interstate Stream Commission John. R. D'Antonio, P.E., State Engineer

July 2006

#### **ACKNOWLEDGEMENTS**

Professor David Gutzler (University of New Mexico), Dr. Gregg Garfin (Climate Assessment for the Southwest, University of Arizona), and Dr. Bernard Zak (Sandia National Laboratories) prepared Section II: Observed and predicted impacts of climate change on New Mexico's water supplies. John Eischeid and Martin Hoerling (NOAA Earth System Research Laboratory) provided the IPCC projection data for that section. Ben Crawford (Climate Assessment for the Southwest, University of Arizona) put together several of the IPCC projection figures. Noah Diffenbaugh (Purdue University) provided regional modeling figures. Special appreciation goes to these individuals who volunteered time from their busy research schedules to assist with developing this report.

An informal "work group," whose names are listed in Appendix A, provided valuable insights and information for the report, as well as recommendations for research, reports and other documents and sources that proved useful in its development.

Deborah Stover, Drought Task Force Programs Manager, and Andrew Funk and Anthony Edwards who were interns at the Office of the State Engineer, provided invaluable research and administrative support.

Anne Watkins, Special Assistant to the State Engineer, served as Principal Author of the report.

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#### **EXECUTIVE SUMMARY**

Governor Bill Richardson, recognizing that the biggest impact of climate change on New Mexico will be its affect on the State's water resources, in his Executive Order 2005-033 directed "The Office of the State Engineer to work with other state agencies, with local and federal agencies, and with the State's research institutions to prepare an analysis of the impact of climate change on the State's water supply and ability to manage its water resources. A report summarizing findings shall be completed no later than July 2006." This report will therefore address only water issues, although it is important to consider it along with the New Mexico Environment Department's December, 2005 report on the impacts of climate change throughout New Mexico.

Global warming and climate change are increasingly understood because a growing number of researchers internationally are contributing to the body of scientific knowledge and to modeling capacity. Although to date little modeling is available that is specific to New Mexico, results from global climate models (GCMs) were utilized for the projections reported in Section II. The impacts to the State are anticipated to be significant for water managers and users, with changes to both supply and demand including:

- ---temperatures have already risen in New Mexico and are predicted to continue to increase:
- ---changes in snowpack elevations and water equivalency;
- ---changes in available water volumes and in the timing of water availability;
- ---increasing precipitation in the form of rain rather than snow due to increasing temperatures;
- ---smaller spring runoff volumes and/or earlier runoff that will impact water availability for irrigation and for ecological and species needs;
- ---milder winters and hotter summers, resulting in longer growing seasons and increased plant and human water use;
- ---increased evaporative losses from reservoirs, streamflows and soils due to hotter, drier conditions:
- ---increased evapotranspiration by agricultural and riparian plants:
- ---an increase in extreme events, including both drought and floods.

Incorporating climate change into water planning has historically been challenging due to the continued level of prediction uncertainty, coupled with the myriad additional pressures faced by water resource planners. Climate change needs to be added as "another pressure" along with population growth, changing demographics, existing climate variability, increasing water demand and availability challenges, land use, species protection and other

ecosystem demands. Adaptive management strategies will need to be devised that are robust and flexible enough to address climate change.

Most of the strategies, policies and tools necessary to manage water resources in the context of climate change have probably already been identified. Incorporation of climate change into New Mexico's water planning may require new modeling and scenarios, and may lead to adjusted priorities and revised timelines, including acceleration of "no regrets" strategies that will also ameliorate the other pressures on the State's water resources.

The State Water Plan (SWP) and many of the State's regional plans already provide a policy framework in which to address climate variability and incorporate many of the policies and strategies that need to be re-evaluated in the context of climate change. Mainstreaming climate vulnerabilities and adaptation strategies into water resource management will be required for comprehensive planning for sustainable development. While the literature on adaptation strategies is still quite limited, there are a variety of recommendations that include both new and revised components of strategic plans and appropriate management strategies. The report outlines some of these as a starting point for discussion of New Mexico's options for addressing climate change:

- Strategic planning within all water-related plans that includes climate change scenarios while recognizing the uncertainties inherent in these predictions and maintaining flexibility within the planning environment to accommodate new modeling and data as it becomes available. Good strategic planning will require:
  - a. improved federal and state water data gathering activities to support sound decision-making;
  - b. increased transdisciplinary and collaborative stakeholder participation in planning and strategy design; and
  - c. integrated regional water planning.
- 2. Highly adaptive management capacity at the watershed scale with particular attention to rangelands, agricultural systems, and aquatic ecosystems.
- 3. Assessing infrastructure vulnerabilities and capacities; improving existing infrastructure and management systems; expanding water supply through new technologies; and developing new approaches to storage.
- 4. Enhanced demand management, conservation and efficiency measures, with special attention to the water/energy nexus.
- 5. Addressing statutory, regulatory and institutional barriers.
- 6. Addressing the role of climate change in meeting the economic, social and environmental goals of sustainable development.

Climate change will likely have a significant impact on the availability of and demand for New Mexico's water during the next century. The key to successful adaptation is a robust planning structure that incorporates highly certain predictions (such as temperature increases) as well as less certain forecasts (such as precipitation changes) into scenarios that can direct implementation of flexible management strategies. The State Water Plan

(SWP) and the regional plans provide a policy framework to which climate change can be added as an additional pressure, albeit a potentially more threatening one. Doing so will better position the State's water resource managers to meet objectives that might otherwise be compromised by changing climatic conditions, while waiting for improved climate predictions may compromise the State's ability to anticipate and capture potential benefits and avoid potential negative impacts.

Adapting to climate change will not be a smooth process and will require multiple management tactics rather than a one-time solution. Given the latest scientific research and modeling on the impacts of climate change, New Mexico could gain substantial benefits from anticipatory stoking of its water management toolbox with proactive policies and clearly beneficial "no regrets" strategies that also alleviate the additional pressures to the State's water resources.

"In the Southwest, water is absolutely essential to our quality of life and our economy. Addressing climate change now, before it is too late, is the responsible thing to do to protect our water supplies for future generations."

Governor Bill Richardson

# I. GOALS, OBJECTIVES, SCOPE AND LIMITATIONS OF THIS REPORT

#### a) Introduction

Governor Bill Richardson has implemented an aggressive climate change initiative for New Mexico. His Executive Order 2005-033 [www.governor.state.nm.us/orders/2005/ EO\_2005\_033] directed that the New Mexico Environment Department (NMED) provide a report on the impacts of global warming on New Mexico by December 31, 2005. That report is available at

http://www.nmenv.state.nm.us/aqb/cc/Potential Effects Climate Change.

The E.O. also calls for a Climate Change Advisory Group (CCAG) to develop a comprehensive program to identify sources and decrease New Mexico's contribution to emissions of greenhouse gases. That will be completed by the end of 2006, and further information about that process can be found at: http://www.nmclimatechange.us.

Recognizing that the biggest impact of climate change on New Mexico will be its affect on the State's water resources, the E.O. also directed:

"The Office of the State Engineer to work with other state agencies, with local and federal agencies, and with the State's research institutions to prepare an analysis of the impact of climate change on the State's water supply and ability to manage its water resources. A report summarizing findings shall be completed no later than July 2006."

This report will therefore address water only, although it is important to consider it along with the NMED report which includes additional information about both water and ecosystem impacts that may not be covered in this document. It has also benefited from the input of an informal work group created to assist with its development (Appendix A) It was developed from information gleaned through published reports as well as informal discussions with water resource managers, planners, modelers, climate experts, and others contemplating the implications of climate change on water resources. As such, it represents a compilation of existing data and educated, scientific opinion on this issue. It does not purport to be an indepth analysis of the issue, primarily because there is not a substantial amount of research specific to New Mexico available on the topic. Nor does it include new research. It is, instead, an initial review of the available information on the impact of climate change on New Mexico's water resources that can be expected based on existing research and analysis.

Global warming and climate change are increasingly understood because a growing number of researchers are contributing to the body of scientific knowledge and to the capacity for models to generate good predictions. However, with few exceptions, very little attention has been paid to the implications of climate change for water policy and management. The report's final section thus includes only a preliminary overview of those areas discussed in the existing literature in which adaptive management strategies will likely be required to limit the extent and severity of adverse and severe consequences from climate change. It is intended to create a framework for dialogue within which policy makers, water managers and the public can begin to incorporate climate change into strategic plans for the State's water future.

## b) Why is this an important issue?

Water is so critical to the New Mexico's quality of life and economic vitality that any impacts to our water resources reverberate across the social, economic and environmental fabric of the State. The anticipated impact of climate change is particularly important since New Mexico is highly dependent on climate-sensitive natural resources (e.g. snowpack, streamflow, forests) and on natural-resource based economic activities (e.g. agriculture, recreation and tourism).

The pressures on water resources in New Mexico are already substantial.

"In the Western United States, the availability of water has become a serious concern for many communities and rural areas. Near population centers, surface-water supplies are fully appropriated, and many communities are dependent upon ground water drawn from storage, which is an unsustainable strategy. Water of acceptable quality is increasingly hard to find because local sources are allocated to prior uses, depleted by overpumping, or diminished by drought stress. Some of the inherent characteristics of the West add complexity to the task of securing water supplies. The Western States, including the arid Southwest, have the most rapid population growth in the United States. The climate varies widely in the West, but it is best known for its low precipitation, aridity, and drought. There is evidence that the climate is warming, which will have consequences for Western water supplies, such as increased minimum streamflow and earlier snowmelt events in snow-dominated basins. The potential for departures from average climatic conditions threatens to disrupt society and local to regional economies." [Anderson, 2005]

In WATER 2025, the Bureau of Reclamation described the realities facing water managers in the Western U.S.: explosive population growth, existing water shortages that will (and already are) resulting in conflict, and aging water facilities that limit management options, noting that crisis management will not be enough to meet these challenges. WATER 2025 called for proactive management of scarce water resources and suggested guiding principles and key tools to address systemic water problems, many of which are relevant to the discussion of managing in the context of climate change. [USDOI, 2005]

The NEW MEXICO STATE WATER PLAN (SWP) created a framework for water management in the State. [www.ose.state.nm.us/water-info/NMWaterPlanning/ state-water-plan] The policies and strategies that it established include many that will be useful in addressing climate change. The SWP already recognizes that New Mexico's climate varies a great deal. Climate change models indicate that such variation can be expected to continue, but that the rate and variation of these changes may be even less predictable and more extreme than in the recent past. The SWP includes multiple responses to climatic variability and change such as active water management, water conservation, urban growth management, development of new water supplies, and watershed and ecosystem protections, all of which often have many more general benefits and can promote longer-term economic and environmental stability for the State. [Meridith, 2002]

Climate change will thus present an additional challenge to management of the State's water resources. Along with population growth, economic development, existing climate variability, recurring drought, and the unpredictable impacts of international geopolitical events, it injects another layer of uncertainty and complexity into the arena in which strategic planning and water policy development occur. "By taking climate forecasts into account and adjusting operational practices to reflect potential conditions, resource managers are better

positioned to meet resource management objectives that might otherwise be compromised as a result of different climate conditions. Climate forecasts may also enable managers to anticipate and capture the benefits associated with possible climate conditions. In both cases, the lead-time provided by the forecasts gives managers the opportunity to anticipate and plan for potential climate-induced changes." [Climate Impacts Group, 2005]

# II. OBSERVED AND PREDICTED IMPACTS OF CLIMATE CHANGE ON NEW MEXICO'S WATER SUPPLIES

Thanks to the following individuals who contributed to this section: Prof. David Gutzler, University of New Mexico; Dr. Gregg Garfin, Climate Assessment for the Southwest, University of Arizona; Dr. Bernard Zak, Sandia National Laboratories.

#### a) Introduction

In the 20th Century global temperature increased by about 1°F, with much of the warming occurring after 1970 [IPCC, 2001]. An increasing body of evidence indicates that much of the increase in temperature is associated with anthropogenic inputs of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and other atmospheric greenhouse gases (henceforth GHGs). The GHGs are trace gases (present in small amounts in Earth's atmosphere) that actively absorb infrared radiation but are much less effective at absorbing solar radiation. Thus GHGs allow sunlight to pass through the atmosphere to the surface, but absorb and re-emit radiant heat emitted from the surface and "recycle" some of that heat back downward. Recycling of infrared radiation creates the "Greenhouse Effect" that keeps the Earth's surface significantly warmer than it would be in the absence of an atmosphere.

Although significant uncertainties remain concerning many aspects and predicted impacts of current climate change, there is no longer any serious debate about several fundamental results [IPCC, 2001; summarized by Gutzler, 2000]:

- Earth's climate is warming rapidly, as can be seen in the worldwide retreat of glaciers, pack ice and snowfields during the 20th Century, continuing today.
- 2) Ice core records show that several principal atmospheric greenhouse gases are now present in concentrations higher than at any time in the last half-million years. The abrupt rise in the concentrations of these gases since the Industrial Revolution is due without doubt to human activities. The concentrations of each of these anthropogenic greenhouse gases continues to increase rapidly; in this century it seems inevitable that CO<sub>2</sub> will reach a concentration more than double its pre-industrial value.
- 3) The direct radiative effect of GHGs is very well understood. There is no doubt that the direct effect of increasing the atmospheric concentrations of GHGs is an increase in Earth's surface temperature.

Similar trends in temperature over the past few decades are clearly in evidence across New Mexico; indeed, warming trends across the American Southwest exceed global averages by about 50%. Since the 1960s, wintertime statewide average temperatures have increased by nearly 1.5°F (Fig. II-1).

It is important to keep in mind that the ongoing warming of global and regional climate is taking place in the context of shorter term weather and climate variability, as well as demographic factors that may increase our vulnerability to climate change. The American Southwest is subject to recurring severe multi-year drought episodes, which occur on average several times per century, as determined from tree ring records spanning the last thousand years (Fig. II-4). These pronounced drought episodes, which seem to a natural component of regional climate, are expected to continue as the climate warms. Meanwhile human population is increasing rapidly in New Mexico, and across the southwestern U.S. and northern Mexico, despite the limited water supply in this arid region.

# b) Overview of climate trends and predictions for New Mexico and the Southwest

In the American Southwest, the impacts of climate variations on water supplies are easily recognizable by simply observing snowpack, reservoir and stream flow levels. Both Global Climate Models (GCMs) and historical trends in temperature, precipitation, and snowpack can be used to assess the recent and potential future effects of climate change on water resources across the Southwest and New Mexico. GCMs indicate that by the end of this century, the American Southwest, and more specifically New Mexico, can expect a significant increase in temperature, resulting in a decrease in snowpack. Precipitation predictions are far less certain, as will be shown in sections II(d) and II(e). The models suggest that even moderate increases in precipitation would not offset the negative impacts to the water supply caused by increases in temperature. Predicted changes in climate variability could also result in more frequent and extreme flooding [Nash and Gleick, 1993].

#### i) Temperature

Climate models predict that increases in temperature in the 21st Century will be greater in the Southwest than the global average, as part of a general tendency for continental interiors to warm up more than oceans or coastal regions [IPCC, 2001]. In the northern part of New Mexico, the largest increases in temperatures over the past several decades have occurred in the winter months, resulting in recent annual average temperatures more than 2° F above mid-20th Century values [Figure II-1]. Recent model simulations suggest accelerated summertime warming in the future [Figs. II-8 and II-11], as will be described below.

#### ii) Snowpack

Climate models predict a trend toward higher freezing altitude and reduction in Western snowpack [Fig. II-2] over the coming decades as a result of rising temperatures [U.S. GCIRO, 2005]. The anticipated higher temperatures discussed above will have several major effects: delay in the arrival of the snow season, acceleration of spring snowmelt, and therefore a shorter snow season, leading to rapid and earlier seasonal runoff [Gleick, 2000]. Annual average temperatures have been rising in the mountainous areas of New Mexico during the winter and early spring [Fig. II-1], which supports model-based projections that snowfall will begin later and total snowfall will decrease, even if winter precipitation stays the same or increases [Lettenmaier, 2004].

Snowpack has been below average for 11 of the past 16 years in the Colorado River Basin and 10 of the past 16 in the Rio Grande Basin [RMCO, 2005]. After one winter of exceptionally abundant snowpack in 2004-05, this trend continued in the winter of 2005-06. Snowfall in New Mexico was far below average last winter and snowpack observations ranged from 40% of average in the upper Rio Chama basin to less than 10% of average over most of the state [SWCO, 2006].

The recent observed decrease in snowpack in the Southwest has coincided with the warming trend. Climate models predict that snowpack in the Southern Rocky Mountains will continue to decline through the 21st Century [Figs. II-3 and II-13]. Increasing temperatures may deplete the water resources in the Colorado River Basin by as much as 40% by the end of the century [Lettenmaier, 2004].

#### iii) Precipitation

Climate models predict a marked decrease during the 21st Century in the ratio of rain to snow in winter precipitation [IPCC, 2001]. The largest percentage increases in precipitation falling as rain are likely to be in the Southwestern U.S. [Felzer and Heard, 1999]. Recent model simulations also predict a decline in total winter precipitation across New Mexico (Figs. II-9 and II-12), but large uncertainties surround these precipitation predictions. Other models show modest increases in winter precipitation. However a recent study concluded that a 7°F increase in temperature in the Colorado River Basin would require precipitation increases of 15-20% above current averages to mitigate the decrease in flows experienced from evaporative losses [Nash and Gleick, 1993]. Additional research has also shown that increases in precipitation along with increased temperatures can result in decreases in runoff [Wolock and McCabe, 1999].

#### iv) Drought

Increasing temperatures, earlier snow melt, and decreasing soil moisture lead to an increase in summertime evaporation, thereby decreasing recycled moisture availability and creating a cycle that perpetuates the "increased intensity, frequency and duration of drought" [WCRP, 2003]. Tree ring-based reconstructions of western droughts over the last millennium show a correlation between warm temperatures and drought, indicating that long-term warming trends could lead to extreme aridity over the western United States [Cook et.al., 2004]. Another reconstruction dating back to 1512 indicates that long-term annual flow in the Colorado River was likely 10% less than the average annual flows measured from 1906 to 2000 [Lettenmaier, 2004].

A representative precipitation history derived from old trees in northern New Mexico [Fig. II-4] shows that recent decades (light blue and green lines) have been relatively wet compared to the long term climatic average (black line). Note that the 1950s drought (red line), the most severe drought in New Mexico in the instrumental record, shows up as a severe episode but is by no means the worst drought in the past 1000 years. This long record, like other reconstructions from different parts of the Southwest, shows that intermittent decade (or longer) droughts have been a recurring feature of Southwest climate for many centuries.

These droughts are currently not predictable, but New Mexicans should assume that severe droughts (like the 1950s, or worse) will continue to occur in the future.

#### v) Flood events

Warming trends will result in shifts and changes in the magnitude of runoff peaks that depend on overall precipitation [Gleick, 2000]. As discussed above, warming at high elevations will decrease winter snowfall and snowpack, increase winter rainfall, and accelerate spring snowmelt, causing probable increases in winter runoff and decreases in summer streamflow [Gleick, 2000]. Increases in summer surface temperatures will likely result in reduced atmospheric stability, increased convection, and a more vigorous hydrologic cycle, resulting in a climate conducive to more intense (but possibly less frequent) storms [Carnell and Senior 1998, Hayden 1999], thereby leading to an increase in flood events. Springtime peak flows could increase significantly and flood events could be earlier and more extreme.

#### c) Global Climate Model (GCM) Predictions

GCMs of several kinds have been developed over the past half century to aid in evaluating what the impacts would be on future climate of various societal choices regarding the use of fossil fuels. The starting point for the use of such models is the definition of "scenarios" for carbon dioxide and other GHG emissions -- effectively, different guesses as to how society might respond to trends in the availability of current fuels (e.g. petroleum) and the potential threat of climate change. The Intergovernmental Panel on Climate Change (IPCC) began its work in 1988, and came out with its first assessment report in 1990 [IPCC, 1990]. In support of its first report, the IPCC defined 6 such emissions scenarios. In support of its third assessment report in 2001, IPCC expanded the number of scenarios considered to 40, categorized by different assumptions about global economic and population growth, as well as global energy policy. Of these, 6 "marker scenarios" were chosen by the IPCC to represent the whole range of potential futures [IPCC, 2001].

Coupled ocean-atmosphere GCMs (CGCMs) running on fast supercomputers represent the state of the art for climate modeling science. Within this category of GCM, more than a dozen models exist, developed and used by various research groups around the world [Meehl et al., 2005]. A suite of such models yielded the results presented in Section II(d). Although they agree on warming in the presence of increasing GHG, each model predicts the evolution of global climate a little differently even when forced by the same GHG emissions scenario. To go from any one of these global simulations to useful regional predictions that take topography into account, it's necessary to couple CGCM results to a higher resolution regional climate model. Results from such a simulation are described in Section II(e).

In considering the effect of climate change on water resources in New Mexico, if one were to follow the IPCC approach, one would run a suite of different CGCMs on the selected IPCC marker scenarios, and couple each run to one (or more) regional model(s). The results could reasonably be expected to span the range of future climate uncertainty. That's well

beyond the scope of the present study. However, there was a recent model-based study of the impact of climate change on water resources in the West that took a more limited but nonetheless in depth look at the issue [Barrett, 2004]. Although it did not focus specifically on New Mexico, the state was included in the modeling domain so useful information can be gleaned from that study. Called the Accelerated Climate Prediction Initiative (ACPI), the Jan-Feb 2004 issue of the journal *Climatic Change* was dedicated to ACPI results.

In ACPI, a single GCM (the NCAR/DOE Parallel Climate Model [PCM]) was forced by a single emissions scenario, a "Business as Usual" (BAU) scenario, for the 21st century. The BAU scenario was developed before the IPCC 2001 scenarios, but it's close to the mean of emissions assumed in those scenarios. The PCM results were "downscaled" to the western region [Leung et al., 2004] using the Penn State/NCAR (National Center for Atmospheric Research) mesoscale model (MM5). For selected river systems, the results were then used to drive the Variable Infiltration Capacity (VIC) macroscale hydrology model to produce stream flow sequences. For the Colorado River basin (including all of Arizona and parts of California, Nevada, Utah, Wyoming, Colorado and New Mexico), annual predicted runoff was 10% lower for simulated 1995 conditions than for historical averages for 1950-1999. For the periods 2010-2039, 2040-2069 and 2070-2098, simulated annual runoff was 14%, 18% and 17% lower than the historical average [Christiansen et al., 2004]. However, because of the timing of the melt (earlier in the spring) and increased evaporation due to higher temperatures, the Colorado River Model used by the USGS predicts that the cumulative total basin storage in reservoirs for these three periods could be reduced by 36%, 32% and 40% respectively [Figure II-5a].

A very similar approach could be used for the Rio Grande using the PCM and MM5 model runs already done, applying the VIC hydrologic model to this different region, and interpreting the results using a Rio Grande rather than a Colorado River model. Such an effort would be far more relevant to New Mexico. In the absence of such research, however, the work already done on the Colorado is at least indicative. It should be pointed out that the average predictions for the focus periods give no indication of the extremes that might occur, so droughts could occur that are far more serious than the averages would suggest. Nor do the results bar extremes on the other end of the spectrum -- floods. Some indication of the range of possible variation can be obtained from the historical record. Between 1906 and 2000, Colorado River annual flow varied between 5.5 million acre feet (MAF) and 25.2 MAF, with an average of 15.3 MAF [Figure II-5b]. Longer term paleoclimate records suggest that the range of possible variation could be much greater yet [Woodhouse et al., 2006].

This section wouldn't be complete without some reference to a climate change scenario which is very different from that discussed above. Model studies have indicated that increasing warming could cause the global ocean currents to reach a "tipping point," and quite suddenly (within a decade or so) cause a drastic change in global climate. The paleoclimatic records from Greenland and Antarctic ice cores indicate that such "flips" have occurred more than 20 times during the last 100,000 years [NRC, 2002]. There is at most an ambiguous indication that such a flip might occur within the planning horizon for water resources in New Mexico [Shiermeier, 2006]. Much less is known about the climate and its potential impact on water resources that might result from such a flip than from the warming scenarios discussed here.

### d) Climate predictions for New Mexico using IPCC global climate models

Climate predictions using GCMs from the forthcoming IPCC AR4 assessment [http://www.ipcc.ch] were used to examine potential changes in temperature and precipitation in New Mexico in the 21<sup>st</sup> century. The models used the Special Report on Emissions Scenarios (SRES) A1B GHG emissions scenario [Nakicenovic et al. 2000; http://www.grida.no/climate/ipcc/emission/index.htm]. The A1B scenario assumes a future world of very rapid economic growth; global population that peaks in mid-century (at approximately 9 billion) and declines thereafter; and rapid introduction of new and more efficient technologies. The A1B scenario has total CO<sub>2</sub> emissions peaking at more than 16 gigatonnes/year (Gt/yr) at mid-century, declining somewhat by the end of the century (Fig. II-6). This results in more than a doubling of pre-industrial atmospheric CO<sub>2</sub> levels by the end of the century. The model experiments included radiative forcing by natural factors, such as changes in solar irradiance and volcanic eruptions, in addition to human-influenced factors such as changes in greenhouse gases and aerosols. The human-influenced factors start with observed data and vary through the course of the 21<sup>st</sup> century based on the assumptions of the aforementioned A1B scenario.

The average of eighteen GCMs forced by the A1B GHG scenario was used in the projections presented here. As discussed in the previous section, there is no way of determining which models best represent the future. The use of a broad average of many GCMs preserves the richness of variability in the complete suite of models, rather than relying on a subset of models that might show faithful representation of present conditions. The GCMs provide projections at rather coarse spatial resolution, depending on the individual model. Spatial resolutions ranged from 1°-3° in latitude and longitude, or approximately 275 km (170 mi.) per side of grid box at 45°N. The entire state of New Mexico is covered by no more than a dozen (often fewer) grid cells in these models.

Averaging the projections required harmonizing the variety of spatial resolutions in the GCMs by downscaling (statistically interpolating) the data to NOAA climate divisions (http://www.cdc.noaa.gov/USclimate/map.html) for the entire United States. Data were kindly provided by Martin Hoerling and Jon Eischeid of the NOAA Earth System Research Laboratory. The climate division data were then combined to create New Mexico statewide temperature and precipitation averages. Specifics regarding the fourth assessment models and projections can be obtained from the Program for Climate Model Diagnosis and Intercomparison (http://www-pcmdi.llnl.gov/ipcc/about\_ipcc.php).

The 18-GCM New Mexico statewide average temperature and precipitation projections (henceforth, *GCM statewide averages*) exhibit some biases compared to observed climate records (Table II-1). The GCM statewide precipitation averages are greater than observed overall, particularly in winter. Water year temperatures are slightly warmer, due to relatively high summer temperatures, despite cooler than observed winter temperatures. The model predictions (below) are presented in comparison to the benchmark of the GCM statewide 1971-2000 averages; however, the aforementioned biases indicate model uncertainties that must be taken into consideration. Moreover, as has been shown by others, GCM temperature projections show greater consistency than precipitation projections (Cayan et al., 2006; Dettinger, 2005).

The GCM NM statewide averages suggest substantial increases in temperature by the end of the century (Table II-2), particularly in summer. Projected GCM NM statewide average temperature increases of over 3°C (more than 5°F) are far greater than temperature increases experienced during the period of instrumental record [Fig. II-1b]. Figures II-7 and II-8 show steady long-term upward trends in annual, winter, and summer temperatures. Trends of as little as 0.04°C/year in summer add up to a considerable overall warming by the end of the 21<sup>st</sup> century. Increases in summer temperature may impact evapotranspiration and soil moisture, as well as energy demand for cooling. The impacts of recurring drought will undoubtedly be exacerbated by temperature increases, as demonstrated during the relatively warm drought of the late 20<sup>th</sup> century [e.g., Breshears et al., 2005].

Annual precipitation, though characterized by greater uncertainty, is projected to decline by 4.8% (29.3 mm) per year by the end of the 21<sup>st</sup> century (Table II-2; Fig. II-9). Increases in summer precipitation (up to several mm/yr by mid-century) are more than compensated for by decreases in winter precipitation (and presumably spring and fall precipitation). Precipitation projections for both winter and summer (Fig. II-10) show multi-decadal fluctuations characteristic of ocean-driven variability in the instrumental and paleoclimate records [Brown and Comrie, 2004; Gutzler et al., 2002; Grissino-Mayer and Swetnam, 2000; Ni et al., 2002]. Even given the high uncertainty in precipitation projections, GCM NM statewide temperature changes are probably substantial enough to have a bearing on the overall composition of winter precipitation – snow versus rain. As in other parts of the West, increasing temperatures may also shift the peak of snowmelt-driven streamflow to earlier in the year, with ramifications for the reliability of water resources [Stewart et al., 2005; Jain et.al., 2005].

The aforementioned temperature projections, though expressed at a coarse spatial scale, are reasonably compatible with estimates from the National Assessment of the U.S. Global Change Research Program [USGCRP, 2000]. However, the overall decrease in annual precipitation [Fig. II-9] is at odds with results from the two models selected by the USGCRP. The steep decline in winter precipitation, especially toward the end of the 21<sup>st</sup> century [Fig. II-10] may reflect a shift in the El Niño-Southern Oscillation phenomenon, due to GHG-induced perturbations in ocean-atmosphere dynamics [e.g., Vecchi et al. 2006]; or it may indicate a tendency for a few overly dry models (e.g., the Australian model; Ron Neilson [Oregon State University] personal communication) to pull the 18-model average down. Given the poor representation of North American monsoon processes in most GCMs [Gutzler et al., 2005], the precipitation projections must be viewed with caution.

### e) Climate predictions for New Mexico using a regional climate model

The global models used in the previous section provide large-scale guidance for potential climate change based on a particular choice of future GHG forcing. As noted, global models typically feature relatively coarse horizontal resolution. Section II(c) outlined a strategy for using higher resolution regional models to improve the description of climate change over limited areas. Diffenbaugh et al. [2005] carried out a climate change simulation by

embedding such a regional model, called RegCM3, within the NASA FV-GCM global model [Atlas et al., 2005].

This simulation was forced by a different GHG emissions scenario, denoted A2 in Fig. II-6. The A2 and A1B scenarios differ primarily in emissions late in the 21st Century. Of course, both of these scenarios represent guesses and many other scenarios are possible, as discussed in Section II(c). All realistic scenarios include significant increases in GHG concentrations in this century, so the principal qualitative difference in the climate change results is simply timing. Scenarios with higher GHG emissions levels generate faster warming trends and more severe climate changes. Therefore the selection of an emissions scenario mostly affects the dates by which a certain level of warming (or snowpack decline, etc.) is reached.

In the Diffenbaugh et al. [2005] simulation, RegCM3 covers the contiguous 48 United States with a horizontal resolution of 25 km. RegCM3 was run for two time periods: 1961-1985, to represent recent climate, and 2071-2095, to represent climate at the end of the 21st Century associated with the A2 GHG scenario. Selected RegCM3 output fields across New Mexico and southern Colorado for these two time periods were kindly provided by Noah Diffenbaugh of Purdue University. Each of the plots shown here depicts the simulated difference between recent climate (1961-1985) and late 21st Century climate (2071-2095).

Fig II-11 shows the change in temperature across the state of New Mexico for

- (a) annual mean conditions,
- (b) the summer season (June-August), and
- (c) the winter season (December-February).

In this model, the A2 scenario generates annual temperature change between 3°C and 5°C (Fig. II-11a), with the magnitude of temperature change increasing inland (toward the north). Recall that observed 20th Century temperature change across the state since the 1960s has been about 1.5°F (Figs. II-1 and II-2), which is somewhat less than 1°C. Therefore this simulation indicates that the relatively rapid warming observed over the past several decades will continue at a greatly accelerated rate during the 21st Century. Spring season results are similar to winter, and fall season is similar to summer (these results not shown).

Precipitation changes for the annual mean, summer and winter (Fig. II-12) are modest compared to temperature changes. The annual average change is generally not statistically significant (Fig. II-12a). The near-zero annual mean change in this simulation results from a slight decrease in summer rainfall (Fig. II-12b) and an offsetting increase in winter precipitation (Fig. II-12c). Other model simulations of 21st Century climate show precipitation changes of different sign, as discussed in Section II(d). Thus, the most predictable climate change in New Mexico forced by increasing GHG is a strong temperature trend toward warmer conditions, not a systematic change in total precipitation one way or another.

As shown in Fig. II-11b, the greatest warming in this simulation occurs in the summer season (consistent with the global model predictions shown in Fig. II-8), with temperature change exceeding 5°C in northeastern New Mexico. Winter warming is considerably less

(between 2° and 4°C in Fig. II-11c), with greatest warming in northwestern New Mexico. One consequence of pronounced summer temperature increase is an increase in both the magnitude and length of extreme heat waves, as described by Diffenbaugh et al. [2005]. In this report we emphasize the effects of climate change on water resources, assuming broadly that precipitation variability from year to year is similar to the current climate, including intermittent drought episodes. Water resources in New Mexico would be greatly affected by the warming trend illustrated in these RegCM3 (and other) simulations, even in the absence of significant precipitation change, because more winter precipitation falls as rain instead of snow, and soil moisture decreases, especially in spring and summer.

The magnitude of winter warming has profound consequences for snowpack throughout the interior of western North America. Fig. II-13 shows the change in snowpack (expressed in mm  $H_2O$  content, commonly referred to as "Snow Water Equivalent" or SWE in observed data) for:

- (a) New Mexico, March 1 average,
- (b) New Mexico, April 1 average, and
- (c) eastern Utah/western Colorado, April 1 average.

The current average date of maximum snowpack in southern New Mexico is around March 1, while snowpack in northern New Mexico and southern Colorado typically reaches its maximum around April 1. Examination of the mean snowpack fields from the model (not shown here) indicate that the solid blue color across New Mexico in climate change panels (a) and (b) can be interpreted to mean that spring snowpack is, on average, nonexistent south of about 36°N in the late 21st Century. In other words, the late 21st Century climate in this simulation includes no sustained snowpack south of Santa Fe and the Sangre de Cristo range.

Snowpack remains in far northern New Mexico and southern Colorado (the headwaters region of the Rio Grande), but is greatly reduced in mass by the end of this century. The April 1 climate change in Fig. II-13c shows reductions in April 1 SWE of 50-200 mm  $H_2O$ , compared to an average in the 1961-1985 simulation of 100-300 mm  $H_2O$  across the San Juan mountains, i.e. a decrease in water mass between one-third and one-half. Some of this decrease results from earlier snowmelt, and some from higher freezing altitude (snow line) during the winter. Spring runoff into rivers and reservoirs is likely to be drastically reduced by the late 21st Century.

Soil moisture changes are most pronounced in the spring (March-May) season, shown in Fig. II-14. The largest changes are seen in northwest New Mexico, where the upper layer soil moisture content decreases by 5 mm  $H_2O$  or more, a decrease of about 20% relative to the 1961-1985 simulation. This change is associated with the decrease in snowpack in the springtime. Soil moisture in the summer season also decreases but less in absolute terms, because soils are dry then even in the current climate.

Evaporation from the surface decreases in the summer season (June-August) in this simulation, shown in Fig. II-15. The red colors represent increased rates of evapotranspiration (ET) of 0.5 mm/d, which is a reduction of 25% or more relative to current

ET rates simulated by the model. This is the result of drier soils and less summer rainfall, and (as noted by Diffenbaugh et al. [2005]) produces a positive feedback on summer temperature increases by reducing the surface cooling effect of evaporation. Interpretation of evaporation changes in this model must be tempered with a significant caveat: the model does not include interactive vegetation, so long-term changes in vegetation that may result from significant climate change are not included in the results [Diffenbaugh et al., 2005].

There are several points worth noting concerning the evaporation changes simulated by the model. First, as discussed above, reduced summer ET simulated by the model is associated with drier surface conditions. Where the surface is not dry (such as the water surface of a reservoir), evaporation rates are certain to *increase*, not decrease, under the 21st Century climatic conditions simulated by this model. Thus depletion of water resources by evaporation from reservoirs would increase. Second, the change in average climate simulated here would greatly increase New Mexico's vulnerability to recurring drought episodes. Drought conditions (such as the state is experiencing now, in the winter and spring of 2006) exacerbate the surface dryness that RegCM3 simulates as a mean condition in the late 21st Century. Warmer temperatures, more extreme heat waves, and a drier surface would make drought episodes more extreme in the changed climate.

The regional climate changes simulated by RegCM3, if realized, would have profound, seasonally varying consequences for the hydrologic cycle across New Mexico. In the cold season (winter and spring), snowpack would be reduced drastically even if total precipitation stays the same or increases somewhat -- and model predictions include the possibility of a reduction in winter precipitation. In the warm season, warmer temperature and drier land surface conditions would raise evaporation rates off open water surfaces and increase vulnerability to drought cycles. These statements remain valid despite continuing uncertainty concerning long-term climatic trends in total precipitation rates in both winter and summer.

Acknowledgements. Jon Eischeid and Martin Hoerling (NOAA Earth System Research Laboratory) provided the IPCC projection data (Fig. II-7 to II-10) and shared insights regarding global climate model output. Ben Crawford (Climate Assessment for the Southwest, University of Arizona), put together several of the IPCC projection figures. Noah Diffenbaugh (Purdue University) generously provided regional model projection figures (Figs. II-11 to II-15).

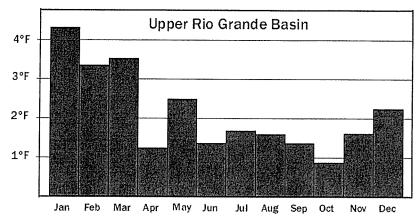
**Table II-1**. Differences between observed (Obs.) and 18-model average temperature (TEM) and precipitation (PPT) for the water year (WY; October-September), winter (DJF; December-February), and summer (JJA; June-August), for the period 1971-2000.

Variable	Obs (in./°F)	Obs (mm/°C)	Model (mm/°C)	Bias (mm/°C)	Bias (in./°F)
WY PPT	14.5 in.	368.6 mm	601.0 mm	232.4 mm	9.1 in.
WY TEM	53.5°F	11.9 C	12.2°C	0.3°C	0.5°F
DJF PPT	2.0 in.	51.8 mm	127.9 mm	76.1 mm	3.0 in.
DJF TEM	36.1°F	2.3°C	0.7°C	-1.6°C	-2.9°F
JJA PPT	6.1 in.	156.0 mm	191.4 mm	35.4 mm	1.4 in.
JJA TEM	71.4 F	21.9°C	24.1°C	2.2 C	4.0°F

**Table II-2.** Changes in temperature and precipitation between the 30-year model reference period (1971-2000) and projections for 30-year periods.

	1971-2000	2001-2030 (change)	2031-2060 (change)	2061-2090 (change)
WY TEM				)
(°C)	12.2	13.1 (+0.9)	14.3 (+2.1)	15.5 (+3.3)
DJF TEM				
(°C)	0.6	1.4 (+0.8)	2.3 (+1.7)	3.4 (+2.8)
JJA TEM				
(°C)	24.1	25.2 (+1.1)	26.5 (+2.4)	27.8 (+3.7)
WY PPT				•
(mm)	601.0	590.0 (-11.0)	589.4 (-11.6)	571.7 (-29.3)
DJF PPT				
(mm)	127.9	127.0 (-0.9)	125.8 (-2.1)	122.4 (-5.5)
JJA PPT				1
(mm)	191.4	189.6 (-1.8)	195.5 (+4.1)	193.0 (+1.6)

Figure II-1a: Average Monthly Temperatures in 1995-2004 in the Upper Rio Grande Basin, compared to 1961-1990 average values. [RMCO 2005]



Data from the climate division series, National Oceanic and Atmospheric Administration. Analysis by the Rocky Mountain Climate Organization. Historical average monthly temperatures are from the period 1961-1990.

Figure II-1b: Five-Year Average Temperatures, 1895 to 2004, compared to Historical Averages [RMCO 2005]

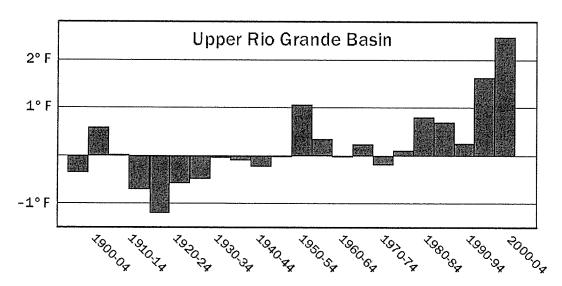


Figure II-2: Possible effects of warming on snowline in higher elevations [Gleick et al., 2000].

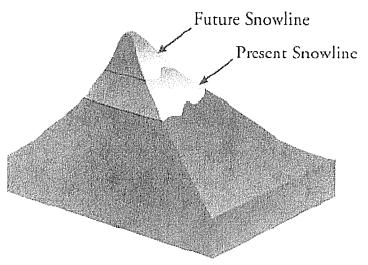


Figure II-3: Percentage change from the 1961-90 baseline in the April 1 snowpack in four areas of the western US as simulated for the 21st century by the Canadian and Hadley models. [USGCRP, 2000]

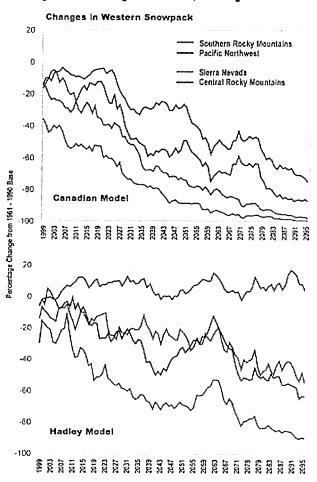


Figure II-4: Precipitation time series for the past millennium for New Mexico Climate Division 2 (north central New Mexico, including the upper Rio Grande Valley). The time series is based on tree ring data within Division 2, and values are expressed as percentage departures from the 1000-year average (thick black line). Average values for three recent decades -- 1983-1993 (a wet period), 1946-1956 (a dry period), and 1996-2006 (the most recent decade) -- are shown as light blue, red, and green lines, respectively.

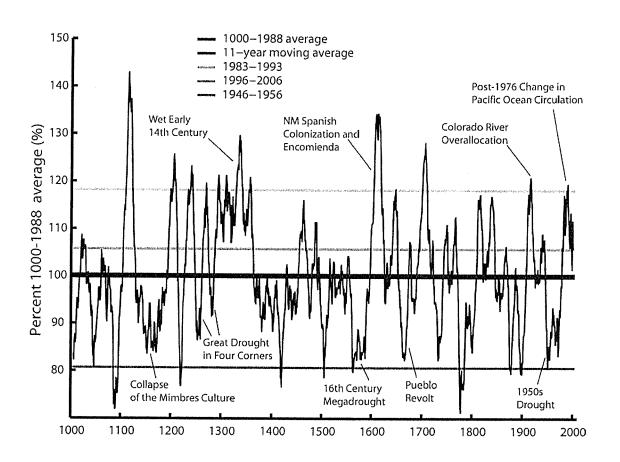


Figure II-5a: Projected changes in average total Colorado River Basin reservoir storage, for downscaled climate simulations of the U.S. Department of Energy/National Center for Atmospheric Research Parallel Climate Model (PCM) based on projected 'business-as-usual' (BAU) greenhouse gas emissions and a control climate simulation based on static 1995 greenhouse gas concentrations, and an ensemble of three 105-year future climate. Simulations for three time periods, and a comparison with observed historical (1950–1999) climate.

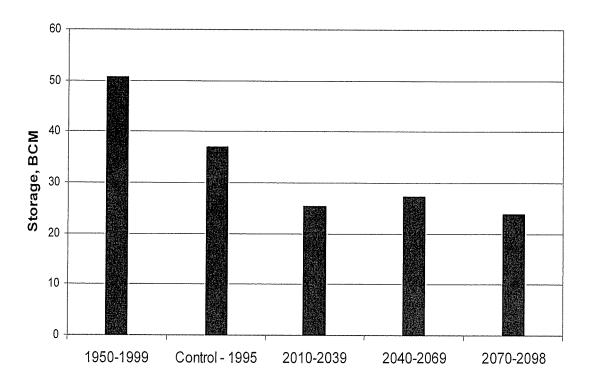


Figure II-5b: Colorado River Basin water year (October-September) annual flow, 1906-2000. Average flow for the period is 15.3 million acre-feet (MAF). The lowest flow in the record is 5.5 MAF in 1977 (Oct. 1976-Sept. 1977); the highest flow in the record is 25.2 MAF in 1984 (Oct. 1983-Sept. 1984). Data courtesy of Dave Meko (University of Arizona) and Jim Prairie (U.S. Bureau of Reclamation).

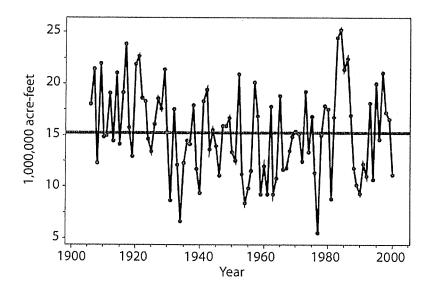


Figure II-6: IPCC Special Report on Emissions Scenarios CO<sub>2</sub> assumptions for the 21<sup>st</sup> century. The atmospheric CO<sub>2</sub> concentrations associated with particular emissions scenarios, shown in this plot, are generated by a carbon cycle model. SRES A1B (green line), the scenario used in IPCC 4<sup>th</sup> Assessment Report projections shown in this section, describes a future world of very rapid economic growth; global population that peaks in mid-century and declines thereafter; new and more efficient technologies are rapidly introduced. SRES A2 (red line), used in the regional model simulation described in section II(e), is similar during the first half of the 21st Century but assumes a higher emissions rate late in the century. Other scenarios (such as B1, the blue line shown here) provide different guesses for 21st Century GHG emissions. Still other, unrealistic scenarios (such as the orange curve assuming no increase at all in CO<sub>2</sub> concentration in the future) are developed by the IPCC for comparison purposes.

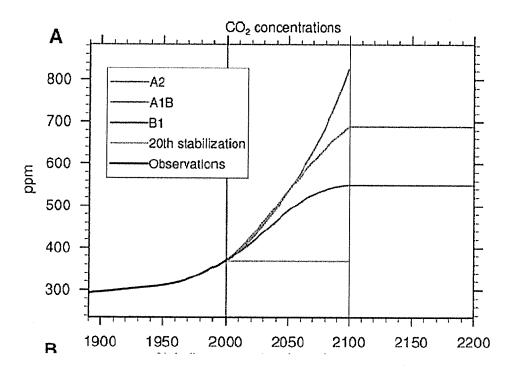


Figure II-7: New Mexico water year (October-September) annual temperature projections compared with model climatology (1971-2000).

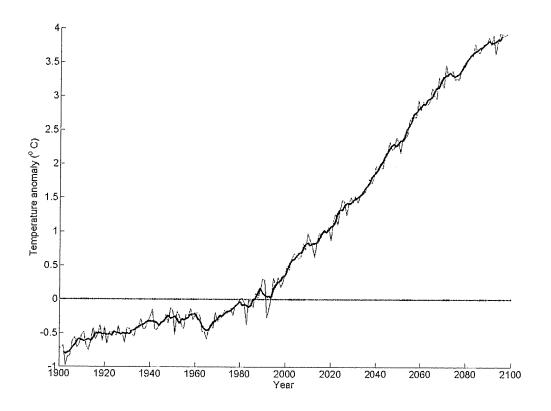


Figure II-8: Simulated New Mexico seasonal temperature changes in the 21st Century for summer (red line; June-August) and winter (blue line; December-February), compared with model climatology (1971-2000).

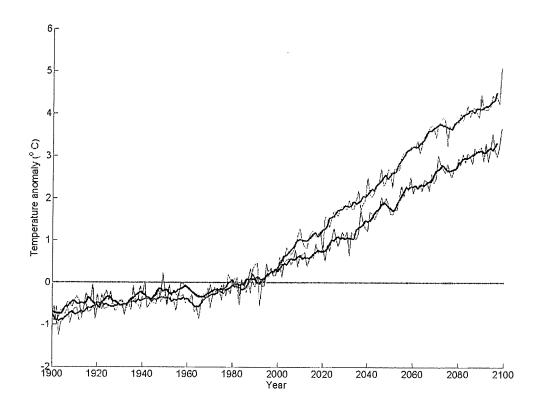


Figure II-9: New Mexico water year (October-September) annual precipitation projections compared with model climatology (1971-2000).

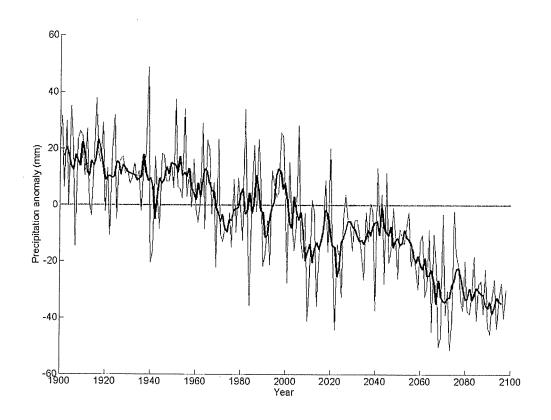


Figure II-10: Simulated New Mexico seasonal precipitation changes in the 21st Century for summer (top, red line; June-August) and winter (bottom, blue line; December-February), compared with model climatology (1971-2000).

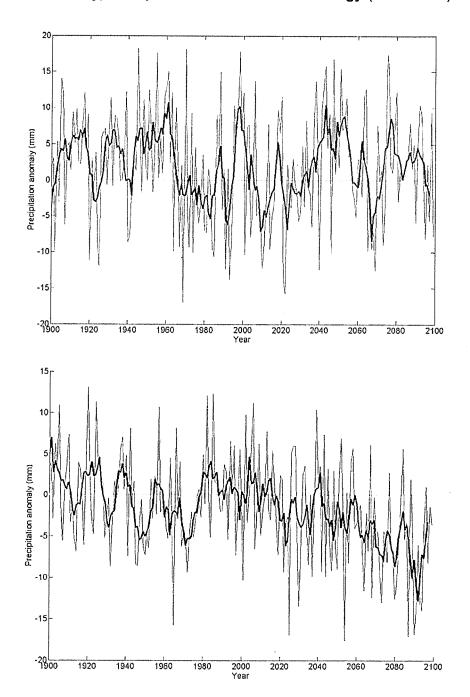


Figure II-11: Simulated change in temperature (°C) from 1961-1985 to 2071-2095 across New Mexico for (a) annual mean (b) summer (June-Aug) (c) winter (Dec-Feb). [Diffenbaugh et al., 2005]

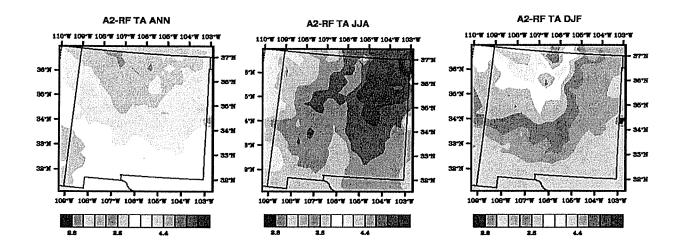


Figure II-12: Simulated change in average precipitation rate (mm/day) from 1961-1985 to 2071-2095 across New Mexico for (a) annual mean (b) summer (June-Aug) (c) winter (Dec-Feb). [Diffenbaugh et al., 2005]. Note that a change of 1 mm/day corresponds to about 14 inches of precipitation accumulated over the course of a year (panel a) and about 3.5 inches for an individual season (panels b and c)

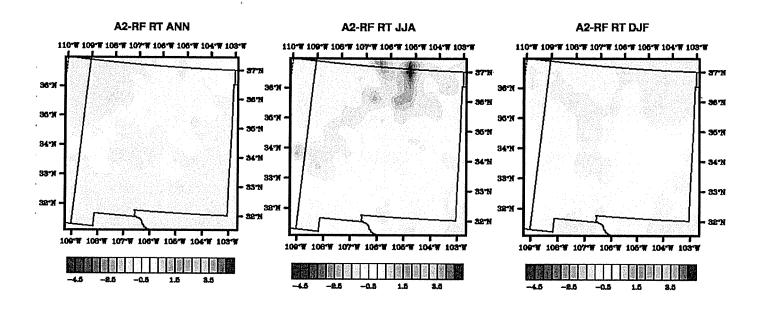


Figure II-13: Simulated change in average snowpack (mm water content in snow) from 1961-1985 to 2071-2095 [Diffenbaugh et al., 2005] for

- (a) state of New Mexico on March 1 each year
- (b) state of New Mexico on April 1 each year
- (c) eastern Utah/western Colorado/southwestern Wyoming on April 1 each year.

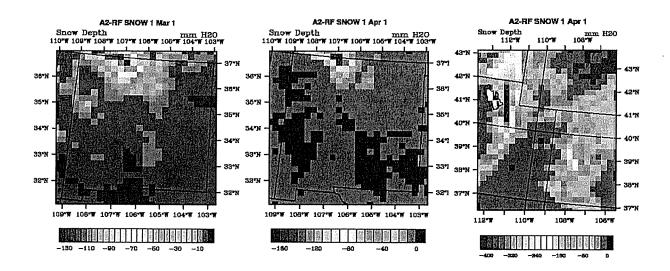


Figure II-14: Simulated change in spring season soil moisture (mm water content in soil averaged from March through May), from 1961-1985 to 2071-2095 [Diffenbaugh et al., 2005].

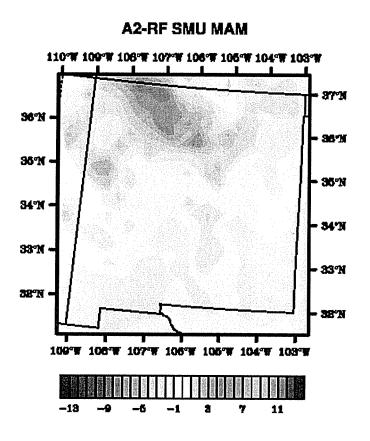
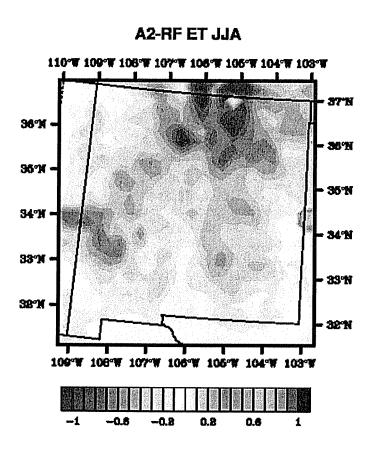


Figure II-15: Simulated change in summer season soil evapotranspiration (mm/day averaged from June through August), from 1961-1985 to 2071-2095 [Diffenbaugh et al., 2005].



# III. INTEGRATING CLIMATE CHANGE INTO WATER RESOURCE MANAGEMENT

#### a) Introduction

Climate change has been discussed primarily at the global scale, and the primary focus of public attention and policy efforts has prudently been on the urgent need for GHG emissions reduction (mitigation) strategies. However, "recognition is increasing that the combination of continued increases in emissions and the inertia of the climate system means that ... even if extreme measures could be instantly taken to curtail global emissions, the momentum of the earth's climate is such that warming cannot be completely avoided." [Easterling, 2004] Therefore, even if CO2 emissions were halted tomorrow, warming will likely persist throughout this century and some degree of adaptation will be necessary. While *mitigation* strategies are necessary to reduce the likelihood or severity of adverse conditions, *adaptation* strategies will be a necessary compliment to reduce the severity of potential impacts.

# b) Climate change and water planning

Climate change has historically had difficulty getting on the agenda of many public and private institutions. The challenge of uncertainty (addressed below) with the resulting difficulty in assessing vulnerabilities, and the limited research and modeling available at the regional or watershed scale, has also been a disincentive. [Climate Impacts Group, 2005] Down-scaling techniques are improving the specificity and accuracy of smaller scale impacts and should support planning at the local level, where the impacts will be felt most acutely and at which adaptive management strategies will need to be designed and implemented. [Hurd, 2006]

Policy makers and managers are also constantly juggling multiple issues of immediate importance and have limited time and resources to take on what appears to be a "new" issue. Climate change is often viewed as one of those issues that can be addressed later when there is more certainty about what is really happening. However, many of the adaptive strategies required to address impacts of climate change will require years to plan and implement, and delaying may increase both vulnerability and ultimately the costs of mitigating those impacts. Often the tools needed to develop adaptive capacity for climate change are the same or similar to those used in current management practices. [Gleick, 2000]

To date, only a few states and local governments in North America have begun to address the impact of climate change on water resources, primarily in the Pacific Northwest due to the predicted dramatic decrease in snowpack coupled with rising ocean levels and potential salt water intrusion. British Columbia has a comprehensive climate change plan that includes both strategies and resource allocation. [British Columbia, 2004] Seattle has a strong climate protection initiative [www.seattle.gov/environment/climate\_preotection], as does Portland [Palmer, 2002]. California has also taken a very aggressive approach to climate change. Its 2005 State Water Plan update addresses climate change "qualitatively," with the stated intent to address it quantitatively in the 2010 update as well as to provide regular updates to the Governor and Legislature. [California Department of Water Resources, 2005 and 2006] While these planning efforts incorporate climate change models and assess impacts, adaptation strategies are essentially still in the developmental stage.

New Mexico's STATE WATER PLAN (SWP) does not specifically address climate change. However, the SWP does comprehensively describe at the policy and strategy level many of the tools that will be needed to manage the State's water resources under a variety of conditions, including those resulting from climate change. WATER 2025 also identifies the most promising tools for dealing with the challenges to western water management, many of which are similar to or will be exacerbated by climate change. [USDOI, 2005] Thus the foundation has already been laid for incorporating climate change as an additional element to the planning process.

### c. The challenge of uncertainty and confidence bounds

"Prediction is very hard, especially when it's about the future."

Yogi Bera

Climate change is impossible to predict with certainty, as is the weather or severity or durations of drought. "Climate varies for multiple reasons, all operating at once, many of which we do not understand well, some of which we may only suspect, and others that we simply don't know...[which have] to be disentangled all at once from a relatively short record of 50 years of good three-dimensional observations and a little over a century of surface observations." [Redmond, 2002] Climate is based on land and atmospheric interactions that create a chaotic system where feedbacks are highly variable and the processes that affect the system at times behave in a non-linear manner. Uncertainties arise from attempts to predict exactly what climate changes will occur in various local areas of the Earth, and what the effects of clouds will be in determining the rate at which the mean temperature will increase. [CaEPA, 2006] "Paradoxically, to understand the driest climates in North America...we cannot fully understand the climate of the Southwest, and how and why it varies, unless we understand the climate of the entire world." [Redmond, 2002]

Tree ring data also indicates that the Southwest has in the past experienced climate swings, including long- term severe drought. [Redmond, 2002] "Future unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve 'surprises'. In particular, these arise from the non-linear, chaotic nature of the climate system..." [IPCC, 1995]

"Reducing uncertainty in climate projections also requires a better understanding of the nonlinear processes which give rise to thresholds that are present in the climate system. Observations, palaeoclimatic data, and models suggest that such thresholds exist and that transitions have occurred in the past ... Our knowledge about the processes, and feedback mechanisms determining them, must be significantly improved in order to extract early signs of such changes from model simulations and observations." [IPCC, 2001]

Uncertainty is inherent to the climate system and cannot be eliminated. However, delaying until all uncertainties are resolved is not viable because some uncertainties will always remain. For example, the degree of impact greenhouse emissions will have on future climatic conditions depends on future decisions and actions by governments and individuals.

"When uncertainty precludes conventional scientific analysis, yet quantitative estimates are needed for use in analysis, it is sometimes possible to obtain the judgments of experts in the form of probability distributions." [NRC, 1999]

---Quantitative assessments of confidence levels [Figure I.1] are representations of researchers' degree of belief in the validity of conclusions, based on collective judgment, observational evidence, modeling results, and theory examined [Gleick, 2000].

---In providing *qualitative* assessments on the state of knowledge, researchers evaluate the level of scientific understanding supporting a conclusion and utilize four

Figure I.1. Confidence Levels for Assessing the Validity of					
Research					
Very High	95% or greater				
<u>High</u>	<u>67-95%</u>				
<u>Medium</u>	<u>33-67%</u>				
<u>Low</u>	<u>5-33%</u>				
<u>Very Low</u>	<u>5% or less</u>				
Source: Gleicl	<u>k, 2000.</u>				

classifications: Well-Established, Established but Incomplete, Competing Explanations, and Speculative.

These quantitative and qualitative assessments of confidence levels can be incorporated by users depending on the specifics of each decision making situation. [Hartmann et. al, 2003] While this environment of uncertainty is complex, climate scenarios developed from modeling are the best

available scientific information about the probable effects of global warming. These tools, coupled with confidence assessments, provide information to support water resource managers and policy makers in the decision making process.

The uncertainty acknowledged by modelers and researchers when projecting climate change includes difficulties in forecasting forcing scenarios, modeled responses to forcing scenarios, and uncertainty caused from missing or misrepresented physical processes in models. Research has shown that better prediction information is developed through feedback between predictions and experience rather than from introducing more sophisticated predictive methods [NRC, 1999]. The processes involved will be iterative, where modelers provide information to decision makers, feedback assessments on the effectiveness of decisions will be provided to both the decision makers and modelers by water managers. It is through adaptive adjustments during this interchange that water managers can document improvements and provide decision makers and researchers with better information.

#### d) Risk management

The every day decisions made by water managers are based on conscious or unconscious risk assessment, where risk is defined in terms of the probability of a particular climatic outcome multiplied by the consequences of that outcome. Consequences will not necessarily vary in direct proportion to the magnitude of climate change due to the possibility of abrupt changes. While New Mexicans are experienced in dealing with climate variability, human-induced climate change is likely to take us outside the range of previous experience and thus require new strategies to cope with emerging situations that cross over previous management thresholds. Decision-makers are regularly called upon to make decisions based on uncertainty (e.g., assumptions about population growth or economic development) with an overall goal of managing future risk from a variety of different factors. Given the scientific uncertainties about the magnitude, timing, rate and local/regional consequences of climate change, water managers will need to determine appropriate responses within a framework that allows for adaptation to new data and changing conditions. [USCRS, 2006]

Climate forecasting raises ethical and legal issues for scientists that relate to risk management. Ethical questions can relate to when and how to issue forecasts, how to deal appropriately with uncertainty, how forecast skils should be developed to achieve an appropriate distribution of benefits, and how ethical beliefs (e.g., concerning the rights of nonhuman species or equity among human populations) do and should affect the development, presentation, and dissemination of forecast information. Legal research questions include assessing case law regarding responsibility for climate, weather, and analogous forecasts as well as the treatment of scientific uncertainty in the legal system, the relationship between impacts and liability settlements, and the role of legal institutions (e.g. water and property rights) in coping with climatic variability and climate forecasts [Stern,1999]

With respect to the onset of global climate change, two schools of thought have emerged regarding the adaptive capacity of water resources and water systems. The first believes that water managers already have the necessary tools to cope with climatic change and argue that key responses to climate change are virtually the same as to existing variability: that is, to upgrade supply-side and demand-side measures and add flexibility to institutions to better cope with social and environmental changes. [Schilling and Stakhiv, 1998]

The other school, however, attaches greater significance to the changing fundamentals being introduced to the climate system. A shift in the climate 'paradigm' increases the uncertainty. No longer can the historical record be relied upon to guide the design, construction, and planning of water projects. This school has less confidence that sufficient time and information will be available prior to the onset of significant or irreversible impacts. Proponents of this view argue that "complacency on the part of water managers may lead to the failure to anticipate impacts that could be mitigated or prevented by actions taken now." [Gleick, 2000]

Policy and managerial responses need not (and should not) wait for better climate predictions. It is already clear that temperatures are rising and that extreme events are becoming more common, so assessing the vulnerabilities of existing management strategies and resource availability given those impacts can proceed without certainty about changes in precipitation. A close look at risk, even without firm quantification, can often lead to optimal solutions that may not be immediately apparent and that may avoid expensive missteps. [Orange County, 2004] Water resource managers already operate within a context of uncertainty about economics, demographics, water supply availability, and other conditions. Climate change is thus not a stand alone issue. It will add an additional layer of uncertainty to the complexity of water resource management in addition to population growth, land use, economic development, species protection, ecosystem demands, and other "change drivers" including peak oil. Managers will thus need robust and resilient planning scenarios and processes, and highly adaptive management structures, to adapt to changing predictions. [Hurd, 2006]

#### e. Adaptive management

Adaptive management strategies are appropriate to consider across the range of sectors potentially affected by changes in water resource conditions. Furthermore, these strategies can take different forms depending on the degree to which they either take a 'wait and see,' reactive stance or an anticipatory perspective in which potential future conditions are taken into account in system planning and design.

In considering the nature and extent of possible climatic changes, reacting to changed conditions can be ultimately more costly than making forward-looking responses that anticipate likely future conditions and events. This is an important consideration, especially with respect to long-lived assets, infrastructure, and institutions such as bridges and dams, settlement and development in water-stressed regions, interstate compacts, urban water reuse and recycling capacity etc., which may be subject to catastrophic consequences as a result of inadequate consideration in design and planning. Such a reactive, "wait-and-see" approach would be particularly unsuccessful in coping with:

- Long-lived investments and infrastructure that may be costly or prohibitive to change in response to climate change;
- Irreversible impacts, such as species extinction or unrecoverable ecosystem changes; and
- Unacceptably high costs and damages, for example, inappropriate development that exposes lives and property to intense weather or drought events. [Smith, 1997]

Proactive adaptation, unlike reactive adaptation, is forward-looking and takes into account the inherent uncertainties associated with anticipating change. Successful proactive adaptation strategies are designed to be flexible and effective under a wide variety of potential climate conditions, to be economically justifiable (i.e., benefits exceed costs), and to increase adaptive capacity (that is how and how well a system adjusts to realized or anticipated environmental changes). [Hurd, 2006]

# IV. TOOLS, POLICIES, AND STRATEGIES FOR ADAPTING WATER MANAGEMENT TO CLIMATE CHANGE.

Most of the strategies, tools and policy responses for managing water resources during climate change are not novel to this issue and have probably already been identified. Generally, responses are needed that will increase management flexibility, develop new supplies, reduce demand, and reallocate water. Accomplishing these goals implicates a variety of strategies and actions including engineering/ technology improvements, coordination among water purveyors, legal and pricing reforms, and robust demand management, to list a few. The incorporation of climate change into the State's planning for water resource management will require new modeling and scenarios, and may lead to changing priorities and revised timelines, especially the accelerated implementation of "no regrets" strategies and possible changes to statutory and institutional structures that will also ameliorate other pressures on the State's water resources.

The discussion in the literature about adaptation strategies is still quite limited, but the emerging literature suggests that there is a clear and defined role for public policy interventions to reduce vulnerabilities and protect natural resources. [Tompkins and Adger, 2005] Throughout the discussions of climate change impacts and potential responses, there are a variety of recommendations for incorporating climate change into strategic planning and for developing adaptive management strategies. Comments at various climate change conferences revolve around the need to take a comprehensive approach and to create multiple planning and adaptation strategies: while there is clearly no silver bullet, there may be "silver buckshot"!

Mainstreaming climate change vulnerabilities and adaptation strategies into water management, disaster preparedness, emergency planning, land use and development planning, and institutional/organizational design will be necessary to integrate climate change adaptation into comprehensive planning for sustainable development. [Agarwala, 2005; Burton and van Aalst, 1999] This section will provide a cursory and by no means complete discussion of some of the strategies and tools for addressing climate change, and will hopefully provide a starting point for discussion of New Mexico's options for incorporating climate change into its water planning and management agenda.

### 1. Strategic planning

The Western Governor's Association, on the recommendation of the Western States Water Council, recently adopted a set of policy recommendations for addressing climate change and other water issues. [WGA, 2006] The general recommendation suggested that, while recognizing the uncertainties inherent in climate prediction, western states and water managers should expand water-related plans to include climate change scenarios and should coordinate with local governments and water purveyors in developing responses.

Lester Snow, Director of the California Department of Water Resources, described this new approach to state water planning in his comments upon the release of California's Water Plan Update 2005, which addressed climate change qualitatively with plans for improved quantitative analysis over the next several years: "This ... represents a fundamental change in the way state government needs to be involved with local entities and interest groups to deal with water issues in the state. The way we manage California's water resources is changing. We need to consider a broader range of resource management issues, competing water demands, new approaches to water supply reliability, and ... to develop

regional water plans that are more integrated...to ensure sustainable water uses and reliable water supplies in the face of uncertainty and change." [WSWC, 2005]

The ability to manage through the uncertainty of climate change will depend on good planning based on good data and modeling scenarios, and on utilizing and expanding the large portfolio of tools and systems in place that allow for robust and easily adaptable management. [Easterling, 2004] Identifying *vulnerabilities* to water supplies, clearly articulating the causes of those vulnerabilities, determining how climate variability and extremes might exacerbate those vulnerabilities, and establishing an analytic framework to identify the best options to correct those vulnerabilities should become part of state, regional and watershed-level water management plans.

# a. Integrate predictions into planning to generate multiple future scenarios for risk analysis, both probability and consequence.

Current modeling, coupled with observed changes over the past decade, provides substantial certainty about temperature increases. While predictions about precipitation cannot be made with the same certainty, it does appear that there will be changes in precipitation patterns due to temperature increases, along with continued high persistence of variability. (See Section II for more detail on predictions for New Mexico.) This will result in changes to the hydrologic cycle (such as increased elevations for snowfall, with resulting decreased snowpack and changes to runoff patterns) which, though not yet specifically predictable, should be incorporated into management planning.

It is critically important to bridge the gap between scientists, policy makers, and water managers so that new climate change model results can be incorporated quickly into both policy and management options. The science and research community will need to prepare assessment and synthesis products to support informed discussion and decision-making about climate variability and change. Improving predictions is likely to depend not only on more sophisticated predictive methods but also on feedback, so that processes are iterative and modelers can improve their ability to provide usable and useful data and results to policymakers and water managers. [NRC, 1999]

# b. Increase federal and state water data gathering activities to serve as the basis for sound decision-making.

To fully understand Southwest climate variations, a more dense network for systematic observation is necessary to identify the smaller scale effect of differences between mountains and adjoining valleys which govern the origin of most streamflow. Supporting expansion of federal data gathering programs, including the National Integrated Drought Information System (NIDIS) [www.nws.noaa.gov/ost/climate/NIDIS] as well as improving state water resource databases is prerequisite to sound decision-making. [Redmond, 2002; WGA 2006]

In addition, inadequate data is available about water availability at national, regional and local levels. "National water availability and use has not been comprehensively assessed in 25 years" according to a U.S.G.A.O. report in 2003. [Whitney, 2006] New Mexico has substantial water usage and demand data that was developed for

the state and regional plans, but there are considerable gaps in knowledge about the State's water resources (especially aquifers).

# c. Increase transdisciplinary and collaborative stakeholder involvement in strategic planning.

A common element of many water supply challenges facing New Mexico are the conflicting needs of people, cities, agriculture, and the environment. Success will always require a collaborative effort among stakeholders, based on recognition of the rights and interests of stakeholders, to maximize the opportunity for innovation and creativity. [USDOI, 2005] The SWP already calls for interagency collaboration and substantial public involvement, to which could be added a public education component that interjects climate change into the discussion about state water policy.

In addition, enhancing ongoing collaboration between state water managers, scientists, federal agencies, universities, and others will insure that the science of climate change is fully understood and incorporated into planning. Conversely, an improved dialogue between scientists and water managers and users is critical to scientists' understanding of data and research needs and to water managers ability to provide feedback loops to scientists to improve predictive capabilities and response analysis. [NRC, 1999]

## d. Improve integrated regional water planning.

The integrated regional water planning (IRWP) paradigm calls for involvement of "myriad water users, purveyors, agencies, governments, organizations and universities to integrate diverse water-related programs that include watershed management, agricultural and urban water conservation, ground water recharge, dam rehabilitation, land use planning, water importation, reuse and recycling, desalination of brackish water supplies, and system interties." [WSWC, 2005] New Mexico has already taken several steps in this direction:

- ---16 regional water plans are either completed or nearing completion, and efforts to integrate these plans into the SWP are underway;
- ---the FOREST AND WATERSHED HEALTH PLAN and the NON-NATIVE PHREATOPHYTE/WATERSHED STRATEGIC PLAN together form the basis of an integrated approach to watershed management;
- ---a water and waste water system collaboration initiative has generated substantial interest in regionalization of those systems, and the Technical Team created to support this initiative has begun to address land use and watershed management and source protection issues.

The overall objective of IRWP is to address issues that individual entities cannot resolve; promote cost effective solutions; leverage investments in existing infrastructure; integrate water management with land use, energy and other resource management issues; and address drought and flooding which are expected to result from climate change. [British Columbia, 2004] Water planning thus needs to become part of a total resource management approach. [World Conservation Union, no date]

# 2. Implement highly adaptive management capacity at the watershed scale

Using climate change science, despite its inherent uncertainties, will require that water planning incorporate vulnerability assessments and utilize an approach that builds increasing resiliency to climatic extremes. States will need to maintain multiple water-related plans, including not only state water plans, drought plans, reservoir management plans, flood plans, and the like, but also forest management, energy, and economic development plans which include water-related concerns. States will also need to coordinate more closely with local governments and water purveyors, which are playing an increasingly important role in water management through land use policies, development of new water supplies, water transfers, and implementation of demand management and water use efficiency programs. [WGA, 2006] This will create increasingly complex planning environments involving multiple stakeholders to enhance ways to manage all water supplies, including groundwater, surface water, and effluent, in a sustainable manner.

Watershed-scale management, such as the State Engineer is implementing through Active Water Resource Management (AWRM), is assuming increasing importance, and devising watershed management plans can not only secure sustainable clean water but also help resolve conflicts during both drought and floods. [British Columbia, 2004] Managing at this scale is also important for resolving the demand for water to support critical ecosystem services. [Whitney, 2006]

Given the importance of agriculture to the State's economy, ecology and heritage, special attention will be required to address the challenge of climate change to the State's rangelands and farming. Similarly, the implications of climate change are more threatening for natural systems, particularly aquatic ecosystems, because it will be difficult for many species to change behavior or migrate, decreasing resiliency and potential for successful adaptation. [Easterling, 2004]

Rangelands: Rangelands are an important part of New Mexico's ecology, economy and heritage, occupying over two-thirds of the surface area of the state with grasslands, shrublands, and savannas. Ranching is nearly \$1 billion industry in the State. [USEPA, 1998] New Mexico's rangelands are managed by a wide variety of people and institutions with many and varied objectives. While livestock grazing currently dominates the decision making on most rangelands, they also perform other valuable ecosystem services such as climate regulation, wildlife habitat, open space, and energy production infrastructure. It is uncommon for any rangeland to be managed for only one use. Rangelands also cover much of New Mexico's watersheds, and can enhance or detract from efficient hydrologic cycle functioning and therefore affect both water supply and quality.

In general, predictions about climate change in the Southwest focus on three major changes over the next several decades: increased temperatures, shifts from summer to winter precipitation and increased variability in both temperature and precipitation within and across seasons [IPCC, 2001]. These changes in the existing climatic regime will alter the geographical extent, the plant composition, and the ecological processes of rangelands, requiring active management approaches for land

managers to remain successful in meeting both commercial and ecosystem needs. [USEPA, 2002]

Managing the State's rangelands effectively during climate change will require an adaptive management approach at all levels that emphasizes monitoring rangeland conditions and flexibility in managerial responses. Adaptive management is a well developed and proven process that has shown positive results in both economic and ecological attributes when correctly implemented. [Easterling, 2004] The State has already created two plans that provide the direction for this new management approach: the FOREST AND WATERSHED HEALTH PLAN and the NON-NATIVE PHREATOPHYTE/ WATERSHED STRATEGIC PLAN. This is especially critical given the demonstrated historical linkages between atmospheric conditions and regional fire activity: increased temperatures with changing precipitation patterns are often precursors to increased regional fire activity, which will place additional stress on water resources. [USGCRP, 2000]

Evaluating the complete range of ecosystem services derived from rangeland management, both public and private, is an important requirement for adaptive watershed management. In addition to the services already mentioned above, it is important to note that increasing temperatures and drought will present challenges to rangeland health. These include likely shifts of plant dominance and structure that are not easily reversed and often result in an increase in invasives as ecological conditions change, as well as the potential for rangeland degradation leading to an increase in blowing dust, detrimental to health and problematic for the State's highway drivers. [USGCRP, 2000] Devising strategies, tactics and operations that will best maintain a full range of services may require such tactics as redirecting conservation program incentives to support and maintain ecosystem services that provide public interest benefits at the expense of short-term economic performance. Those currently managing rangelands and/or deriving their livelihood therefrom will need to be involved early and consistently in discussions about maintaining and improving rangeland health during climate change, and additional resources will likely be required to support the management approaches required to enhance the ecological functioning of these lands. [Brown, 2006]

**Farming:** Crop production in New Mexico is a \$500 million industry. A warmer climate, with less snowfall, more winter rain, and an earlier spring runoff could mean decreased ability to store water for use later in the summer when demand peaks, as well as increased evaporation. Farmed acres in the State could decrease as much as 25% due to these pressures. [USEPA, 1998]

Agricultural systems are managed, so farmers have multiple adaptation options including revised plant/harvest schedules, crop rotations or changes, and different tillage practices. However, agricultural systems display high sensitivity to extreme climatic events (floods, wind storms, drought) and to seasonal variability (frost dates, rainfall patterns). Increased rainfall intensity can increase soil erosion, along with degraded water quality from increased movement of agricultural chemicals and waste into water bodies. Coupled with increased temperatures, it can result in increases or changes in pests and invasive species. [Adams, 1999]

Agricultural policies will need to address both the challenges and opportunities of climate change while also adapting to other pressures. Although the role of soils and

crops in carbon sequestration is not yet fully understood, it should play a role in farming techniques as well as crop selection. The opportunity for New Mexico's growers to provide feedstock for production of ethanol and biodiesel may open new markets to support changing crop patterns. [Ebinger, 2006]

Policies will also need to address the impact of the peaking of world oil production, which will result in higher oil prices and a liquid fuels problem for the transportation sector. [Hirsch, 2005] The agricultural sector is heavily dependent upon diesel fuel: for transportation of fertilizers and pesticides (most of which are produced from petroleum), and for transportation of products to markets. U.S. consumers are also heavily dependent upon petroleum for transportation of food. The combined challenge of "peak oil" and food production has increased interest in the development of local food production and urban agriculture, and calls for careful evaluation of pressures to move agricultural water to other uses.

Aquatic ecosystems: Aquatic and wetland ecosystems display high vulnerability to climate change. Changes in water temperature and shifts in timing of runoff will change aquatic habitats, resulting in species loss or migration as well as novel and unpredictable interactions of new combinations of species. [Fish, 2005] Stream management practices will have to accommodate these new threats to aquatic species, increasing Endangered Species Act (ESA) and threatened species challenges. [Poff et. AI, 2002]

## 3. Infrastructure and technology options

The SWP includes a policy and strategies for improving the use of and for enhancing water supplies through continued improvements in technology. Many western universities, as well as the national laboratories, have research programs that could be focused on practical applications of new and existing technologies to improve water management and expand water supply. [WGA, 2006] Climate change will add an additional pressure to the other variables that already challenge water managers dealing with aging infrastructure and distribution demands.

There are three major areas in which science and technology should play a major role in addressing this and other U.S. water challenges [Whitney, 2006]:

- a. Improving use of existing infrastructure: Increased application of management systems (such as Supervisory Control and Data Acquisition, or SCADA; meter telemetry) will improve the efficiency of infrastructure management, in addition to providing the feedback loops and quick response time required for adaptive management.
- b. Expanding supply through new technologies for water reuse, desalination, weather modification and expanded use of lower quality water: Implementation of new technologies may require regionalization in order to achieve the scale necessary to justify investments, and additional research will be necessary to determine effectiveness and feasibility (for weather modification, for example). A comprehensive study of untapped but impaired water supplies in the State could focus development in those locations with a high probability of water demands exceeding supplies, as well as those most likely impacted by climate change. [U.S.D.O.I., 2005] Costs for many of

these are decreasing, while experience from implementing new technologies is providing direction for more efficient and effective use in the future. NOTE, however, that both increasing energy costs and the need to decrease greenhouse gas emissions are major considerations in determining an appropriate role for these new technologies. (see Part 4 below)

c. Developing new approaches to water storage: New Mexico already loses a substantial amount of water through evaporation. Improving both surface and groundwater storage alternatives, including aquifer storage and recovery, are key areas for technological advancements.

Infrastructure vulnerability assessment: Safe engineering design depends upon a probability analysis of historically observed hydrologic events. One of the anticipated impacts of climate change is an increase in extreme hydrologic events. both flood and drought. [Groisman et. al., 2001] Rain has increased in the U.S. by 7% in three decades; heavy rain events of more than 2 inches a day have increased 14%, and storms dumping more than 4 inches a day have increased 20%. [Epstein, 2006] Historic records may therefore not reflect the magnitude of future events. The "return period" for hydrologic events is also based on the average, historicallyobserved elapsed time between occurrences of different magnitudes, and this may also change significantly with climate change. Assuring that existing infrastructure will withstand both more extreme and greater frequency events will require vulnerability analysis and possibly cautionary retrofit. Engineering manuals that provide design standards for hydrologic analytical methodologies will need to be revisited and revised to insure that anticipated changes in the magnitude of hydrologic events are incorporated into designs for new infrastructure. [Hernandez, 20061

Reservoir management: Warming and loss of snowpack will impact operations of many of the state's reservoirs. More precipitation as rain, coupled with the retreat of snowpacks to higher elevations, will increase reservoir inflows during the winter and early spring months, resulting in empty flood control space previously maintained during winter months being filled earlier with runoff. Especially with the potential for extreme flood events, more annual runoff is likely to go through reservoirs earlier in the year, decreasing the amount available for hydropower and irrigation uses later in the year. Reservoir managers will need to search for physical, regulatory, and operational flexibilities to accommodate these changes. [CaDWR, 2006]

## 4. Demand management, conservation, and efficiency

The IPCC, in each of its assessments to date, has noted that water demand management and institutional adaptation are primary components for increasing flexibility to meet the uncertainties of climate change. [IPCC 1995, 2001] Innovative water conservation practices could decrease water use, and management innovations could increase efficiency with limited environmental impact. [CaDWR, 2006] Most agricultural irrigation water delivery systems were built in the early 1900s. Lining or enclosing of canals where appropriate, rehabilitation of irrigation system infrastructure, and application of new automated and remote-controlled water management technologies using low-cost solar-powered components, while requiring significant initial investment, can modernize existing systems and improve efficiency of water delivery, often with substantial savings. [USDOI, 2005]

Most urban (i.e. non-agricultural; the term "urban" will be used for the municipal, domestic, commercial, industrial and institutional sectors) water systems were built in the middle of the last century. A combination of aging infrastructure and increasing demand is generating need for replacement or upgrading of systems, providing the opportunity not only for decreased conveyance loss but also for integrated regional water and waste water system design that can incorporate such opportunities as use of pre-treatment water for golf courses and other non-potable demands, thereby optimizing the use of and extending the existing water supply.

**Urban sector:** The fastest growing demand for water is the urban sector. with water supplies limited and water rights at a premium. The majority of New Mexico's drinking water systems are rural, and much of the population depends upon community water systems or domestic wells. Climate change. particularly long term drought, can result in loss of water sources, as well as a rise in turbidity and in levels of contaminants regulated by the Safe Drinking Water Act (SDWA). It will also exacerbate existing challenges, including uncertain future demand, changing demographics, unanticipated treatment costs, changing quality regulations, infrastructure maintenance and upgrades. and developing new water supply options. [Palmer and Hahn, 2002] Some of the climatic events that are most disruptive to water systems will be compounded by climate change: high temperatures and drought (which increase demand); high winds and electrical storms (that cause electrical outages); and heavy precipitation and flash floods (that may cause breakage or exposure of infrastructure, overload the capacity of waste water systems, and impact water quality and turbidity). [Carter and Morehouse, 2003]

Confronting the additional pressure of climate change with existing challenges is already leading to collaboration among small water systems. Regional planning and infrastructure development will need to integrate drinking water, waste water, source water protection, new supply development, and demand management for sustainability. A State water conservation plan for this sector would establish policies and strategies to decrease both domestic and commercial use, along with appropriate State programs to facilitate and accelerate implementation of practices with the greatest potential for successful reduction of water use. Such a plan should include such accepted strategies as metering; per capita usage goals; subdivision, development and construction code changes to encourage water efficiency and grey water reuse; and land use guidelines to encourage waterefficient development landscaping. The State's "Our Communities. Our Future" initiative has developed a multi-pronged approach that includes many policies and statutory/regulatory recommendations to support sustainable water supplies. [Hughes, 2006]

Agricultural sector: Most irrigation systems are already implementing some efficiency and conservation techniques. [King,2005] Resources for such improvements could be targeted to areas where additional water is needed for environmental or other purposes. Re-evaluation of current farming technologies and cropping patterns, particularly perennial crops such as orchards, will need to be done in the context of climate change to assist farmers with appropriate adaptations.

Water/Energy nexus: "Water and energy are interdependent," according to Mike Hightower of Sandia National Laboratories. Much of energy production requires water, and water pumping and treatment require a lot of energy. [WSWC, 2006] Increased demand for energy (for cooling, anticipated with temperature increases) leads to increased demand for water that is unlikely to be offset by decreases to winter demand (from reduced heating). [Smith and Tirpak, 1989; Sailor and Pavolova, 2003] Increased demand for potable water leads to increased demand for energy.

Providing water for multiple purposes is also energy-intensive. The California Energy Commission estimates that providing water to the State results in an average of 44 million tons of carbon dioxide emissions. End uses of water, including heating for domestic, commercial and industrial operations, also consume energy, as does waste water treatment. Consequently, any reductions in energy consumption related to water will decrease GGEs. [CaDWR, 2006]

There is thus a strong link between energy and water conservation, with opportunities to achieve both through collaboratively planned projects. Including energy savings can improve the economic justification for water conservation projects and may be one of the best ways to reduce energy use and therefore emissions. Water conservation can lower energy use and energy bills. Water recycling is a highly energy efficient water source. Both water and energy policymakers should give water conservation higher priority as a mutual benefit. [Cohen et. al, 2004]

#### 5. Statutory, regulatory and institutional barriers.

"States should evaluate and revise as necessary the legal framework for water management to the extent allowable to ensure sufficient flexibility exists to anticipate and respond to climate change." [WGA, 2006] WATER 2025 also identified that water management could be improved through removal of institutional barriers. [USDOI, 2005] An extensive literature on the important role of institutional capital to plan, facilitate, implement, monitor, and sustain adaptations to climate change has noted that appropriate institutional mechanisms may be absent and that long-lived institutions may be unable to accommodate the restructuring necessitated by adaptations. [Young, 2002; Easterling, 2004] In the Colorado River Basin, for example, measurements of the economic effects of hypothetical changes in climate and precipitation indicate that much of the total damages result from the current inflexibility of the Colorado River Compact. [Loomis et.al., 2003] The Endangered Species Act (ESA) and the National Environmental Policy Act (NEPA) may limit habitat management options; river restoration and species protection may not be compatible or synergistic; and managing aquatic ecosystems in arid lands with climate uncertainties may be compromised. [Cowley and Sallenave, 2006] Water policies, including pricing and inadequate quantification of water rights as well as related issues such as land use, can inhibit conservation and limit valuable flexibility in market-oriented transfers. [Easterling, 2004]

While certain to send a shudder through water attorneys, managers, and multiple stakeholders, pressures on water resources (drought, increased demand, changing regulatory requirements, sustainable development) have already highlighted areas

where new approaches are required. Climate change will add to that pressure and call for re-evaluation of existing structures.

#### 6. Sustainable development.

Sustainability is often defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." Sustainable development involves a comprehensive integration of economic, social and environmental goals that will need to incorporate the impacts of climate change. [Robinson et.al, 2006] Climate change will add an additional pressure, and an unpredictable variable, to those already faced by New Mexico in meeting its water needs. However, climate change and sustainable development policies can reinforce each other; for example, the reduction of non-renewable energy consumption and conservation practices that also reduce greenhouse gas emissions. [Swart, 2003]

While the published literature on the impacts of climate change is substantial, that on the links to sustainability is still scarce. That on adaptation strategies is also limited, other than general descriptions of options and opportunities briefly described in this report. However, much of the response to climate change will necessarily be local, because that is where the impacts will be felt. [Easterling, 2004]

#### V. CONCLUSION

"I have found that plans are useless, but that planning is priceless."

President Dwight Eisenhower

New Mexico's water future will be determined by water demand and availability of our water resources. Climate change will likely have a significant affect on both. Continued and exacerbated variability, coupled with changes in amount, form (rain vs. snow), location, and intensity/duration of precipitation events are anticipated results of climate change, and these changes will have serious consequences for water managers. [Smith, 2006]

There is a clear and defined role for public policy intervention in adapting to climate change. [Tompkins and Adgar, 2005] The key to successful adaptation is a robust scenario-based planning structure. The STATE WATER PLAN provides a policy framework to which climate change can be added as an additional pressure, albeit perhaps a potentially more dangerous one. It and the State's regional plans already include many of the strategies required to address climate change. Identifying likely changes and quantifying the range of potential impacts will allow the State to identify and evaluate adaptation options, and to compare costs and benefits against both "no action" risks as well as strategies already in place to meet additional demands. It will set the stage for moving forward with those "no regrets" strategies that clearly address both climate change and other challenges, while continuing to investigate other pathways that may be less clear.

Building the adaptive capacity required to manage climate impacts before they occur is the ultimate objective of such planning. Building such capacity will evolve over time as new modeling results become available and additional defendable adaptation opportunities become evident. Water resource planners and managers will need to incorporate monitoring, re-evaluation and adjustment of policies and strategies into management activities to respond to climate changes and additional pressures and demands. Doing so will better position water resource managers to meet objectives that might otherwise be compromised by changing climate conditions. [Climate Impacts Group, 2005]

Adaptation is not likely to be a smooth process or free of costs, and it is by definition ongoing rather than a one-time solution. [Easterling, 2004] Planning need not and should not wait for "perfect" climate predictions on precipitation---action can be initiated now based on what is known: that temperatures are increasing with resulting changes in precipitation and that extreme events are likely to become more common.

Given the latest scientific research on the impacts of climate change, it appears that there would be some urgency as well as substantial benefits from stoking New Mexico's adaptive capacity with proactive policies and strategies in anticipation of what is likely to come. As Governor Bill Richardson said on February 28, 2006, when announcing the Arizona/New Mexico collaboration on the Southwest Climate Change Initiative, "In the Southwest, water is absolutely essential to our quality of life and our economy. Addressing climate change now, before it is too late, is the responsible thing to do to protect our water supplies for future generations."

### APPENDIX A: CLIMATE CHANGE WATER IMPACTS WORK GROUP

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# Climate variability and projected change in the western United States: regional downscaling and drought statistics

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Abstract Climate change in the twenty-first century, projected by a large ensemble average of global coupled models forced by a mid-range (A1B) radiative forcing scenario, is downscaled to Climate Divisions across the western United States. A simple empirical downscaling technique is employed, involving model-projected linear trends in temperature or precipitation superimposed onto a repetition of observed twentieth century interannual variability. This procedure allows the projected trends to be assessed in terms of historical climate variability. The linear trend assumption provides a very close approximation to the time evolution of the ensemble-average climate change, while the imposition of repeated interannual variability is probably conservative. These assumptions are very transparent, so the scenario is simple to understand and can provide a useful baseline assumption for other scenarios that may incorporate more sophisticated empirical or dynamical downscaling techniques. Projected temperature trends in some areas of the western US extend beyond the twentieth century historical range of variability (HRV) of seasonal averages, especially in summer, whereas precipitation trends are relatively much smaller, remaining within the HRV. Temperature and precipitation scenarios are used to generate Division-scale projections of the monthly palmer drought severity index (PDSI) across the western US through the twenty-first century, using the twentieth century as a baseline. The PDSI is a commonly used metric designed to describe drought in terms of the

local surface water balance. Consistent with previous studies, the PDSI trends imply that the higher evaporation rates associated with positive temperature trends exacerbate the severity and extent of drought in the semi-arid West. Comparison of twentieth century historical droughts with projected twenty-first century droughts (based on the prescribed repetition of twentieth century interannual variability) shows that the projected trend toward warmer temperatures inhibits recovery from droughts caused by decade-scale precipitation deficits.

#### 1 Introduction

Century-scale climate change projections are often depicted as large scale differences in time-mean fields such as temperature and precipitation (IPCC 2007a). Such projections are of great interest scientifically, but are widely acknowledged to be of very limited direct use for local and regional policymakers and other stakeholders (IPCC 2007b). For applications other than climate research, climate change projections must be downscaled spatially and temporally to much higher resolution than can be provided by global coupled models carrying out centuries-long integrations at relatively coarse resolution.

Multiple approaches to downscaling have been implemented in order to fit particular applications (e.g. Karl et al. 2009). Catchment-scale hydrologic projections may require daily time resolution and spatial resolution on the 10 km scale, for example (Wood et al. 2004). Here we describe an especially simple approach to downscaling on a somewhat larger scale. The goal is to put climate change into context with interannual variability (Hulme et al. 1999), to illustrate the effects of projected climate change at the Climate Division scale, on the order of (100 km)<sup>2</sup>.

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This scale is larger than a small watershed (hence too coarse for many hydrological applications), but smaller than the global and continental scales exhibited by projected long-term climate trends simulated by global models (IPCC 2007a). Operational seasonal climate forecasts in the US are carried out at approximately the temporal and spatial resolutions represented by monthly mean, Climate Division averages. The twentieth century instrumental record supports long-term monitoring of temperature, precipitation and drought at this scale. Thus the Climate Division scale represents an important link in the concept of 'seamless prediction' extending from daily weather out to long-term climate change (Palmer et al. 2008).

The analysis described in this paper has two purposes. One is to illustrate and discuss the utility and limitations of an extremely simple and easily understood technique for implementing downscaling appropriate for interannual variability studies. We will emphasize the simplicity of the approach. This is especially useful for purposes of presenting a 'scenario' of climate change to nonspecialist stakeholders. Our experience dealing with the public across the Southwest suggests that the concept of a 'scenario' as defined in climate change research (i.e. just one of a large set of possible future outcomes) may be familiar to climate scientists but is not easily understood by nonspecialists. The particular approach to downscaling interannual variability described here lends itself to easy interpretation as a scenario, as opposed to a deterministic forecast.

The second purpose is to exploit the structure of interannual variability prescribed in this scenario to extend and complement previous studies of twenty-first century drought in the western US. The trend toward drier hydrologic conditions in southwestern North America in the twenty-first century has been the subject of considerable study already using both observations (Seidel et al. 2008; Barnett et al. 2008) and future projections (Burke et al. 2006, Seager et al. 2007; Hoerling and Eischeid 2007; Sheffield and Wood 2008). The particular algorithm described in the next section for adding climate variability to model-projected climate change lends itself to studying future droughts, because the observed interannual/decadal variability of temperature and precipitation associated with twentieth century droughts is exactly repeated in the future scenario. We can therefore ask how the 1930s Dust Bowl, or the 1950s drought in the Southwest, would evolve in the context of a warmer climate. Section 3 addresses this issue using the palmer drought severity index as a metric of drought. These results can be compared with twenty-first century projections of mean soil moisture (Wang 2005), persistent soil moisture anomalies (Sheffield and Wood 2008) and palmer drought index (Burke et al. 2006) derived using a purely model-based approach.

## 2 Observed and projected temperature and precipitation

The climate change scenario developed here is based on two sources of data. First, we use observed monthly temperature and precipitation time series for the twentieth century (through the end of 2007), derived by NOAA from cooperative observer sites and averaged into US Climate Divisional values by the National Climatic Data Center (NCDC) (Guttman and Quayle 1996). Second, a projection of twenty-first century climate change is derived from an average of 18 global climate models, based on the CMIP3 archive (http://www-pcmdi.llnl.gov/ipcc/about\_ipcc.php; Meehl et al. 2007). The global model simulations considered here were all forced by the A1B scenario of future anthropogenic radiative forcing, which assumes a relatively mid-range storyline of greenhouse gas increases (IPCC 2007a). Monthly ensemble averages of temperature and precipitation were statistically interpolated to US climate divisions by M. Hoerling and J. Eischeid of the NOAA Earth System Research Laboratory. These data were used previously in an assessment of projected climate change in New Mexico (NMOSE 2006).

For many purposes it is essential to consider the magnitude of projected long-term changes relative to interannual variability (Hulme et al. 1999), and that is a major goal of this study. However global climate models currently exhibit quite disparate changes in short term climate variability in response to long-term trends. An example of such uncertainty is the El Niño-southern oscillation (ENSO) cycle, which has a profound effect on the interannual variability of western North America, but which evolves in a warming climate very differently depending on the details of the ocean-atmosphere coupling incorporated in a particular model (Joseph and Nigam 2006; Vecchi et al. 2008). For this study we choose to keep just the simulated, averaged long-term trends generated by an ensemble of global coupled models, and add to the trend interannual and decadal variability taken from historical data, using observed twentieth century variability repeated in the twenty-first century.

Quantitatively each future annual value x(t) for year t (t ranging from 2008 to 2100), where x is either temperature or precipitation for a particular month and Climate Division, is calculated from:

$$x(t) = C + T(t) + A(t - 100)$$
(1)

where C=1971-2007 observed climatological average of x, T(t)= linear trend in x from the 18-model average of A1B-forced simulations for the period 2008-2099, and A(t)= detrended anomaly value of x from exactly one century prior to year t. Terms C, T and A are each calculated separately for each calendar month. Assumptions and



limitations associated with each of the terms on the right hand side bear careful consideration.

Term C provides the starting point for the projected scenario. By anchoring climate model projections in this way, systematic mean biases in the climate model output are eliminated. Such biases form one of the principal concerns in any downscaling algorithm (e.g. Wood et al. 2002). Term C also ensures that future trends start from current observed conditions, which may be rather different from longer term (century scale) averages. Purely model-based downscaling may not include this property.

Term T(t) is the only term in (1) that incorporates climate model output; C and A(t) involve historical data exclusively. We argue that T represents the component of the greenhouse-gas forced ensemble model simulations that is most robust, while neglecting the components of model output that are less reliable, such as interannual variability from individual models. Studies that consider century-scale differences in precipitation, temperature or soil moisture (e.g. Wang 2005) focus just on T.

Alternatively, one could replace the time-varying trend term T in (1) with a fixed value of climate change  $\Delta T$  to explore the consequences of interannual variability derived from historical data (term A) in a climate with a different mean state. Such a procedure has been denoted the "Delta" or " $\Delta$ -change" method, and has been used to evaluate climate change impacts that are associated with in extreme conditions at some prescribed time in the future (see CCSP 2008 for a brief review). By specifying a time-dependent climate change T(t) instead of a fixed value of  $\Delta T$ , the scenario based on (1) describes the emergence of the climate change signal from higher frequency interannual variability described by term A.

For this study we assume linearity in the climate change signal described by T(t), although it would be easy to implement a higher order fit to the model-average change. Figures 1 and 2 will illustrate two examples showing that the assumption of linear change provides an excellent fit to the A1B-forced average temperature and precipitation throughout the twenty-first century.

The final term in (1), denoted A(t), introduces temporal variability to the linear climate change signal by a simple repetition of twentieth century interannual variability. This procedure therefore assumes that the statistics of climate variability remain stationary in the twenty-first century, even while the mean climate shifts significantly as described by T(t). Both recent observations (Groisman et al. 2005, 2008; Alexander et al. 2006; Allan and Soden 2008) and model simulations (Tebaldi et al. 2006; IPCC 2007a; Allan and Soden 2008) strongly indicate that variability is increasing, and is expected to increase further as climate warms, so the assumption built into (1) in term A(t) is likely to err on the conservative side. Introducing

nonstationary higher moment statistics could be accomplished either through dynamical downscaling (e.g. Leung et al. 2004; Diffenbaugh et al. 2005) or a more sophisticated empirical technique (e.g. Wood et al. 2004). We are exploring such modifications to the scenarios presented here, and we take care with nonspecialist audiences to point out the probable underestimate of future variability using this approach.

In this study we consider temperature and precipitation changes derived from only one of many IPCC emissions scenarios, A1B. The A1B scenario is commonly used as a 'midrange' emissions projection, in between the IPCC storylines associated with 'business as usual' and the storylines associated with aggressive emissions policies or slower growth of energy consumption (IPCC 2007a). A more complete treatment of climate change uncertainties would include an envelope of multiple scenarios (e.g. Sheffield and Wood 2008). One way to interpret the uncertainty in the choice of scenarios is as an acceleration/ deceleration of the projected change. Temperatures that are reached by 2075 in the A1B scenario would be reached sooner in a business-as-usual scenario, or later in an aggressive-policy scenario. Such interpretation is somewhat oversimplified but consistent with inspection of temperature change maps associated with different scenarios (e.g. Fig. 10.8 in IPCC 2007a, or the plots on page 29 of Karl et al. 2009). This simplification neglects potentially important nonlinear threshold effects or impacts that may be dependent on rates of change, rather than on just the magnitude of climate change at any particular time.

Examples of divisional scenarios using this procedure are shown in Figs. 1 and 2 for temperature and precipitation in New Mexico Climate Division 2 (Northern Mountains Division, hereafter NM2), and Nebraska Climate Division 3 (Northeast Division, hereafter NE3; see Fig. 3 for these locations). Figure 1a shows summer and winter time series of NM2 temperature. By construction, the process of averaging multiple simulations smooths out simulated interannual variability and decreases the sampling error (but not systematic errors) associated with determining long-term trends. A linear trend clearly provides an excellent fit to the projected twenty-first century change, consistent with the assumption underlying term T in (1).

For the scenario shown in Fig. 1b, the only feature kept from the model simulations is the linear trend fit to the temperature projection for 2008–2099. For the period 1901–2007 (to the left of the dashed vertical line), historical NM2 data are plotted. The observed sequence of detrended interannual anomalies from the twentieth century data is then repeated—exactly one century later—starting in 2008, superimposed on the projected summer and winter trends for 2008–2100, to form the climate change scenario to the right of the dashed line. Note that

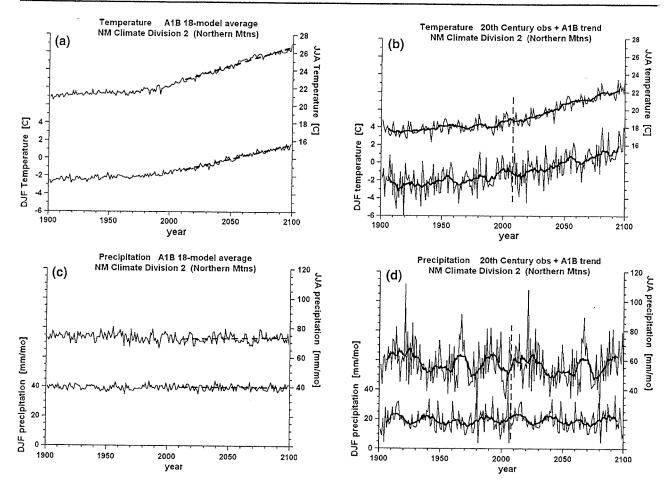


Fig. 1 Time series of annual temperature (°C) and precipitation (mm/mo) for the DJF winter season (lower lines) and JJA summer season (upper lines) for the twentieth and twenty-first centuries in New Mexico Climate Division 2 (NM2, Northern Mountains, shown hatched in Fig. 3). Thin lines in each panel show annual values; thick lines are 11-year running averages. a Simulated temperature, averaged over 18 global coupled models forced by the A1B greenhouse gas scenario. Dashed black lines show a linear trend fit to the time series for the period 2008–2099. These trends have values of +3.3°C/century in winter and

+4.3°C/century in summer. **b** Winter and summer temperature as in **a**, with interannual variability derived from observations For years 1901–2007 (*left of vertical dashed line*), values are actual observed climate divisional data. For years 2008–2099 (*right of dashed line*), values are derived by adding twentieth century interannual variability to the twenty-first century simulated trend shown in **a**, using Eq. 1. **c** Like (**a**), but for winter and summer precipitation. The trends have values of -0.11 (mm/month)/century in winter and +1.6 (mm/month)/century in summer. **d** Like (**b**), but for winter and summer precipitation

the model average for the twentieth century (Fig. 1a) exhibits a significant warm bias of about  $3^{\circ}$ C in the summer relative to observations (Fig. 1b). As noted above, this bias is removed from twenty-first century values by adding the model-derived trend to term C on the right hand side of (1). The projected temperature trends in NM2 are  $4.3^{\circ}$ C/century (summer, upper curve) and  $3.2^{\circ}$ C/century (winter, lower curve).

The trends in precipitation are small by comparison, and display considerable variability from model to model (IPCC 2007a; Seager et al. 2007). The slight downward trend in NM2 winter precipitation during the twenty-first century in the 18-model average of A1B-forced simulations (Fig. 1c) is characteristic of the climate change signal in subtropical latitudes in the IPCC simulations (IPCC

2007a; Fig. 3). Even a modest downward precipitation trend could potentially have profound importance for the hydrologic cycle in semiarid regions, when combined with the increase in evapotranspiration associated with the much more pronounced projected temperature trend (Seager et al. 2007).

The winter trend in Fig. 1c is -0.07 (mm/mo)/century, which is statistically indistinguishable from zero. In the scenario developed from (1), the projected twenty-first century decrease in NM2 is less than the short-term decadal increase that was observed at the end of the twentieth century and continues through 2007. Thus average winter precipitation during 2070-2100 in Fig. 1d actually exceeds the observed twentieth century average, despite the small downward trend exhibited during the twenty-first century



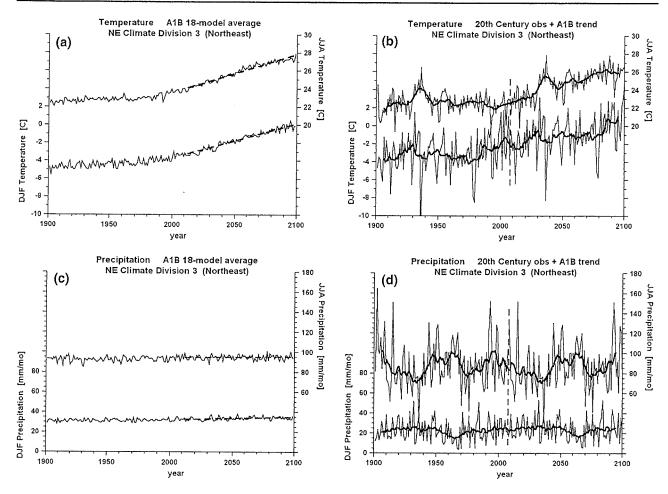
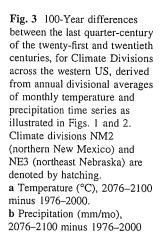
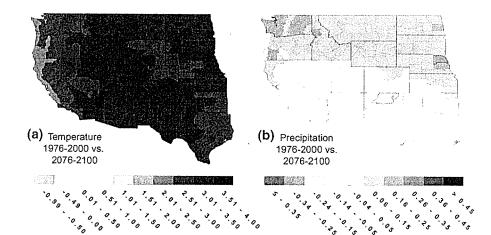


Fig. 2 Like Fig. 1, but for Nebraska Division 3 (NE3, Northeast NE, shown hatched in Fig. 3). The 2008–2099 linear trends in temperature shown in a have values of +3.9°C/century in winter and +4.2°C/

century in summer. The corresponding precipitation trends in c are +2.4 (mm/mo)/century in winter and +1.1 (mm/mo)/century in summer





in the A1B ensemble average and applied in our scenario after 2007. In other words, term C in (1) has a bigger effect on late twenty-first century precipitation than term T in this particular time series.

As in NM2, the summer temperature trend in NE3 exceeds the winter trend somewhat (Fig. 2a). Addition of observed twentieth century interannual variability (Fig. 2b) serves to emphasize the summer temperature trend because



warm season variability is smaller than cold season variability. Unlike NM2, NE3 exhibits an upward trend in precipitation in both winter and summer (Fig. 2c). Nevertheless, the trends are small relative to interannual variability (Fig. 2d), as was the case for precipitation in NM2 (Fig. 1d).

The instrumental record provides a basis for establishing the century-scale historical range of variability (HRV), an important metric used by the ecological community (Landres et al. 1999). By mid-century, the summer season in NM2 exhibits a higher average temperature every year than any summer season ever observed in the instrumental record, i.e. summer temperatures quickly rise outside the climatic HRV. Winter temperatures, in contrast, do not fall outside the range of observed twentieth century winters until much later in the twenty-first century. This seasonal difference occurs in part because summer trends are larger in magnitude than winter trends (Fig. 1a). More importantly, however, interannual variability is much larger in winter than in summer, so that "cold winters" in the midtwenty-first century exhibit average temperatures comparable to temperatures experienced in the current winter climate.

The linear trends in NE3 temperature are comparable to the NM2 trends, but in NE3 the trends are somewhat less pronounced because interannual variance is larger there in both winter and summer. Late twenty-first century temperatures in NE3 are not consistently outside the twentieth century HRV in this scenario. Of course, the foregoing statement is potentially sensitive to both the magnitudes of twenty-first century trends (subject to uncertainties associated with the choice of emissions scenario, unpredicted climate forcings other than greenhouse gases, and general global modeling uncertainties), and the magnitude of future climate variability (prescribed here to remain constant).

The spatial distribution of the temperature and precipitation trends across the western United States is shown in Fig. 3, showing the difference in values for the last quarter century of the twentieth and twenty-first centuries. This figure is similar (as it should be) to the western US results based on A1B simulations shown in Figure 11.12 in the IPCC AR4 Working Group I report (IPCC 2007a). Both NM2 and NE3 are in the region of large annual temperature trends characteristic of the continental interior (Fig. 3a). However the precipitation trends in these Divisions have opposite signs: NM2 is in the region of modestly decreasing precipitation exhibited across the southwestern tier of states, although the trend in NM2 is smaller in magnitude than in some other nearby Divisions (Fig. 3b). In general, the decrease in projected precipitation in southern states noted in other studies (Seager et al. 2007; IPCC 2007a) based just on model-simulated trends is mitigated in the hybrid scenario presented here because, as

noted above, the late twentieth century was generally a wet period which affects the starting point of future trends.

Division NE3 is located within the northern tier of states exhibiting increases in precipitation, in both winter and summer, in the A1B ensemble average. Based on the gradient in precipitation change seen in Fig. 3b we would expect that corresponding drought statistics could be different in the northern and southern halves of the US.

#### 3 Projection of palmer drought severity index values

To explore the surface water budget changes implied by these projections, we have generated twenty-first century palmer drought severity index (PDSI) scenarios for the western US from them. The PDSI uses Thornthwaite's method to account for the effects of evapotranspiration on soil moisture, controlled by temperature and precipitation (Palmer 1965; Alley 1984; Dai et al. 2004). Lockwood (1999) has shown that use of Thornthwaite's method could lead to overestimates of potential evapotranspiration in a warmer climate, one of several caveats that must be applied to our results. Soil moisture is accounted for by a two-layer model in which the top layer has a field capacity of 1 inch and does not exchange water with the bottom layer until saturated. Runoff occurs only when both layers are saturated, and all precipitation during a month is either used to meet evapotranspiration and soil moisture demands or is lost as runoff (Heim 2002). Uncertainties in projected PDSI calculations are discussed further in the Appendix.

The PDSI was designed to quantify drought in regions where precipitation is the primary moisture source. It does not account for downstream transport of water (Heim 2002) or for delayed arrival of precipitation to soil caused by melting snow or frozen ground (Alley 1984). Other limitations of the PDSI include its arbitrary divisions of drought severity classes and its simplified treatment of soil moisture such as the absence of groundwater dynamics (Alley 1984; Dai et al. 2004). Despite these drawbacks, the PDSI is a very common and well-recognized index of drought, generated weekly and monthly in real time by operational climate monitoring services and is used widely by stakeholders.

The monthly time series of temperature and precipitation for each Division were used as input to the PDSI algorithm available online from the NCDC. Using these data we reproduced NCDC's published Divisional time series of twentieth century PDSI. We then ran the program forward in time using the scenarios described in Sect. 2 for each Division. Because climate changes significantly during the two-century period of record, these results are potentially sensitive to the choice of the standardization period (the so-called CAFEC values, "climatologically



appropriate for existing conditions", Heim 2002) used to normalize the PDSI values. We will show results using 1931–1990 as the standardization period. This is the same period used by NCDC to calibrate its published PDSI values. Prior to 1931 the divisional temperature and precipitation values are not directly calculated from divisional data; instead they are based on regressions applied to statewide monthly means of temperature and precipitation (Guttman and Quayle 1996).

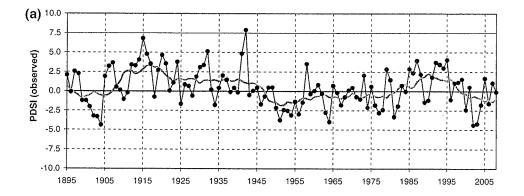
Annually averaged PDSI time series for NM2 and NE3 are shown in Figs. 4 and 5, respectively. Annual PDSI values generally range between -4 and +4 during the twentieth century. Extreme values outside this range are very rare, by construction. The panels in Figs. 4 and 5 are aligned so that annual values one century apart can be compared. The repetition of interannual variability from the twentieth century after 2007 is easily seen in the PDSI values. For example, the historic wet years of 1941 and 1942 in NM2 appear as consecutive, extremely positive PDSI years in Fig. 4a, and these years also appear as positive (but less so) values one century later in 2041–2042, in Fig. 4b.

As temperature increases during the twenty-first century, extreme negative values of the PDSI become the new climatological norm for NM2 (Fig. 4), after a transition toward drier (more negative) conditions in the surface water budget. Only one annual PDSI value greater than

zero occurs in the NM2 record during the entire second half of the twenty-first century, and the average PDSI value during the latter half century is around -5.0, lower on average than any individual annual value in the entire observational record through 2007. This climatic regime shift toward much drier conditions in the Southwest is consistent with the projected climate change described by Seager et al. (2007).

The historical drought of record in the twentieth century in NE3 is the Dust Bowl era of the 1930s, manifested as six consecutive years with annual PDSI less than -2.5(Fig. 5a). By construction, the interannual variability associated with the Dust Bowl is repeated in the decade of the 2030s. In this case the repeated twenty-first century drought is affected very little (as measured by PDSI) by the projected climate change. This is because, relative to NM2, the temperature trend is slightly smaller, the precipitation trend is upward which counteracts increased temperature in the surface water budget, and the repeated drought occurs in the 2030s instead of the 2050s so the effects of projected climate changes are less pronounced. Note that NE3 experienced another four consecutive years of drought conditions from 1988 to 1991. While severe, this drought was both less intense and shorter than the Dust Bowl drought of the 1930s. The repetition of the later drought from 2088 to 2091 is considerably more intense (more negative PDSI), but still shorter in duration, than the

Fig. 4 Time series of annual (October-September) dimensionless PDSI values for Division NM2 (shown hatched in Fig. 3), derived from the monthly temperature and precipitation values shown in Figs. 1b, d. The thick line depicts an 11-year running average. a Twentieth century observations (1895-2007). b Twenty-first century projection (2008-2100), with the last 13 years of observed values (1995-2007) repeated from a



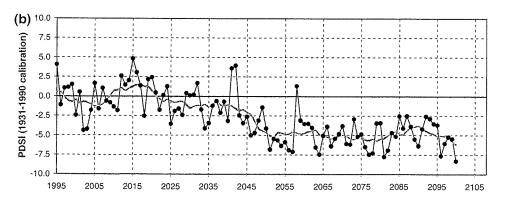
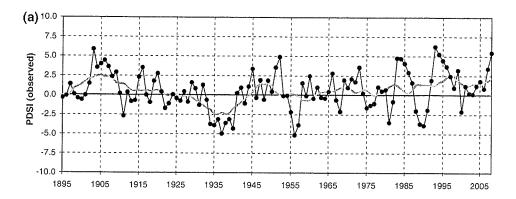
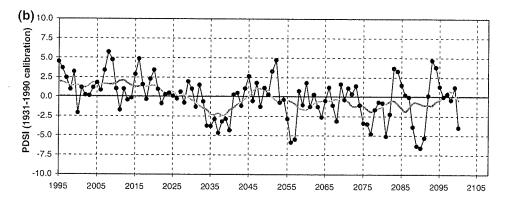




Fig. 5 Like Fig. 4, but for NE3, derived from the monthly temperature and precipitation values shown in Fig. 2b, d





repeated Dust Bowl of the 2030s. Average PDSI in the late twenty-first century in NE3 is less than corresponding values a century earlier, but the difference is much smaller than exhibited in NM2.

For comparison, Burke et al. (2006) reported PDSI trends (averaged over global land areas) of -0.3/decade for the first half of the twenty-first century, decreasing to -0.56/decade in the second half of the century. The straight line fit to twenty-first century values shown here have slopes of -0.70/decade for NM2 (Fig. 4) or -0.25/decade for NE3 (Fig. 5), but the time evolution of these curves is far from linear. Half-century PDSI trends in NM2 or NE3 are strongly influenced by the timing of major droughts in the observed twentieth century record which are repeated in the twenty-first century, and much of the twenty-first century decreases in PDSI in Figs. 4 and 5 occur as rather abrupt declines associated with the onset of major decade-scale drought episodes.

The overall evolution of PDSI across the western US during these two centuries is summarized in Fig. 6, which shows successive 25-year averages for the twentieth and twenty-first centuries for each Climate Division in the western US. The twentieth century (upper four maps), based on observations, exhibits alternating periods of modestly positive and negative values. Periods of extreme drought did not persist through multiple decades anywhere in this domain, so averaging over 25-year epochs reduces the severity of any particular drought episode. Alternation

of drought between the northern and southern states is apparent in the historical data (Brown and Comrie 2004). The 1951–1975 period (panel c) is the driest in the twentieth century, with the entire Southwest exhibiting average PDSI less than zero while the northwestern half of the domain had average PDSI values slightly greater than zero.

Large decreases in average PDSI occur in the twenty-first century across the West in this scenario (Fig. 6e–h). Instead of subregional drought, with a north–south dipole in drought severity, the entire interior western US (except for a few isolated Divisions in the northern half) exhibits a tendency toward lower PDSI values. Maps of the 2051–2075 and 2076–2100 time periods are outside the historical range of twentieth century drought conditions. Seasonal differences in PDSI departure between corresponding intervals of the two centuries are apparent (but not shown here). The summer months of June, July, and August exhibit larger decreases in PDSI than the winter months, consistent with the greater temperature trend in summer (such as the example shown in Fig. 1) and the greater sensitivity of the surface water budget to temperature-driven evaporation in summer (Weiss et al. 2009).

The increased spatial extent and frequency of "severe" drought (quantitatively defined as PDSI <-3.0, using the twentieth century to define the climatological normal distribution of PDSI), is illustrated in Fig. 7. During the twentieth century, only small regions experienced severe drought in more than 20% of all months during any 25-year



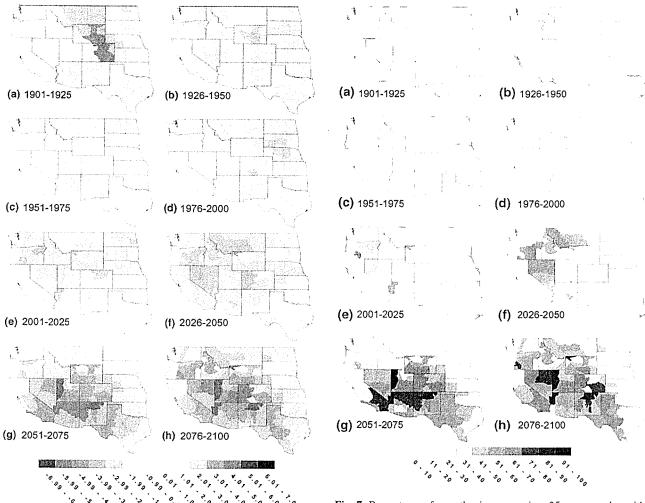


Fig. 6 25-Year average PDSI values for each Climate Division in the western US, for successive epochs in the twentieth and twenty-first centuries

epoch. For example, areas of the Pacific Northwest and the upper Plains states were drought-prone during the 1926–1950 epoch (Fig. 7b), while the Southwestern states experienced very few drought months. Conversely the northern tier of states experienced very little drought in 1951–1975 while the Southwest was much more drought-prone (Fig. 7c). In the twenty-first century, however, both the area and frequency of severe drought increases so that, by 2076–2100, nearly the entire western US (with the

There is no apparent epoch-scale recovery in the Southwest from the constructed mid-twenty-first-century drought (Fig. 7g, h) as occurred in the twentieth century (Fig. 7c, d). Furthermore the surrounding states—essentially the entire interior west, from the Cascades and Sierra Nevada ranges eastward to the Rocky Mountains and

exception of western Oregon and Washington) experiences

severe drought during >20% of all months.

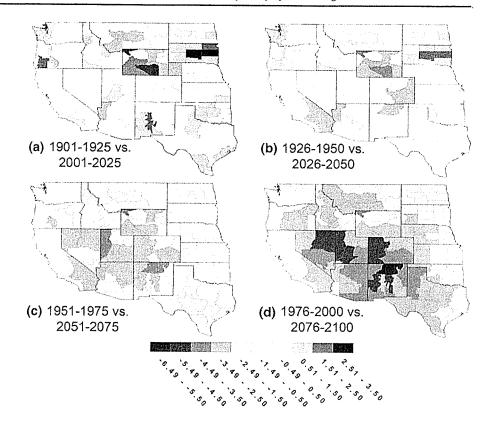
Fig. 7 Percentage of months in successive 25-year epochs with PDSI  $\leq$  -3.00. PDSI values < -3.00 represent "severe drought" in the current climate (Heim 2002)

southern Plains—also become drought-prone (by twentieth century standards) during the latter part of the twenty-first century.

The combined effects of projected temperature and precipitation trends on PDSI are shown explicitly by taking 100-year differences in PDSI successive 25-year epochs (Fig. 8). The early years of the twenty-first century are affected by the late twentieth century climatology, which influences both the first seven years of the epoch and the following 18 years of projected values via term C on the right hand side of (1). Regions for which the recent observed climatology is wet, such as parts of South Dakota or New Mexico, tend to show positive PDSI values in 2001–2025 relative to 1901–1925 observations. Recent upward trends in precipitation have, so far, compensated for upward temperature trends in preventing large-scale drought conditions from developing across the US (Easterling et al. 2007).

The effects of the initial climatology decrease with time, and by the latter half of the twenty-first century the large

Fig. 8 100-Year differences in 25-year average PDSI across the western US for successive epochs



scale projected temperature trend drives average PDSI values toward negative (drought-prone) conditions throughout the western US. The largest century-scale trends in PDSI are seen in southwestern states, where generally wet conditions in the late twentieth century (Fig. 6d) are replaced by widespread, severe drought values a century later (Fig. 6h). The PDSI time series for NM2 (Fig. 4) illustrates this trend for one representative Division; Fig. 8 indicates that similar results hold throughout the Southwest.

The plight of the Southwest in this scenario is emphasized by comparing the 25-year average difference in PDSI for the latter halves of the twentieth and twenty-first centuries. In the twentieth century, the Southwest underwent a decade-scale transition from drought-prone conditions in the 1950s to very wet conditions in the 1980s and early 1990s. This transition is often associated with a shift in the Pacific Decadal Oscillation in the late 1970s (Mantua et al. 1997; Gershunov and Barnett 1998; McCabe and Dettinger 1999; Gutzler et al. 2002). Average PDSI values increased sharply toward positive values between the third and fourth 25-year epochs in observations (Fig. 9a).

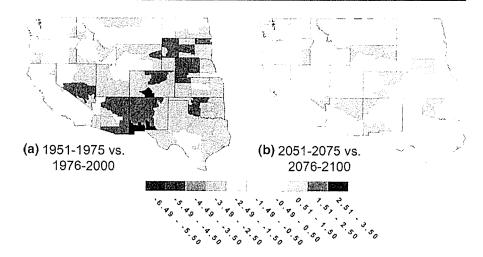
One century later, term A in (1) repeats the interannual and decadal variability for the late twenty-first century. But the sharp projected temperature trend alters the surface water budget so that PDSI values fail to recover in the late

twenty-first century (Figs. 7, 9b). As discussed previously (Seager et al. 2007; Hoerling and Eischeid 2007) the Southwest "dries out" as the result of the warming trend, and a repetition of the decadal climate shift of the late 1970s is insufficient to enable drought recovery in the late twenty-first century.

The tendency for increasing temperature trends to inhibit recovery from decade-scale drought conditions on the Divisional scale is illustrated in Fig. 10, again using NM2 and NE3 as examples. The figure shows successive 25-year annual averages of temperature, precipitation and PDSI for the twentieth and twenty-first centuries. The first four 25-year epochs are based entirely on observed twentieth century data; the 2001-2025 epoch is a mix of early twenty-first century data and the first 18 years of projected data; and the final three epochs are entirely projected, with twentieth century interannual variability repeated. Temperature increases monotonically in NM2 throughout the 200-year period, while the Dust Bowl years in NE3 are associated with a peak in temperature for the 1926-1950 average. The great twentieth century droughts in NM2 and NE3 drive 25-year average minima in precipitation in the third and second epochs, respectively, of the twentieth century. These minima are repeated in the twenty-first century, superimposed in NE3 (but not NM2) on an increasing precipitation trend derived from the A1B ensemble average.



Fig. 9 Differences in 25-year average PDSI values for successive epochs in the late twentieth and twenty-first centuries. a 1976–2000 minus 1951–1975. b 2076–2100 minus 2051–2075



The corresponding 25-year average PDSI values closely parallel concurrent precipitation fluctuations in the twentieth century, with a small downward decrease apparent in NM2 (Fig. 10a) associated with the observed upward trend in temperature. This close relationship between average precipitation and PDSI weakens over the course of the twenty-first century, as the effects of increasing temperature drive PDSI toward negative values in both Divisions regardless of the repeated multidecadal variations in precipitation. PDSI remains negative on average following the constructed droughts of the 2050s in NM2, and the 2030s in NE3, despite the recovery in precipitation following both drought episodes. The upward trend in precipitation in NE3 over the latter half of the twenty-first century is insufficient to bring the average PDSI values up above zero. Widespread drought in the late twenty-first century drought in this scenario is largely temperature-driven.

#### 4 Discussion

Three key assumptions built into this downscaling procedure are associated with each term on the right hand side of (1). The implications and limitations of these assumptions are assessed term-by-term as follows.

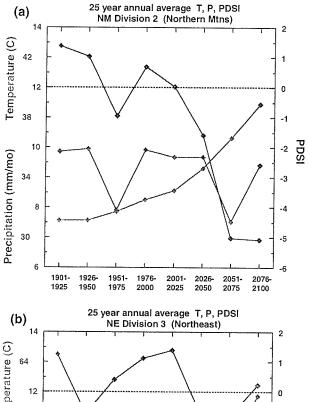
Using the current observed climatology as an anchor for twenty-first century projections (term C) can make a significant difference in the interpretation of modest projected trends. In the American Southwest, for example, the late twentieth century was very anomalously wet before the onset of the turn-of-the-century drought (Swetnam and Betancourt 1998; Groisman et al. 2004). These conditions are reflected in positive PDSI values across the four-corners states (UT, CO, AZ, NM) in Fig. 6d, and in the strong precipitation-driven recovery from mid-century drought conditions (expressed as negative PDSI) during the last

25-year epoch of the twentieth century (Fig. 9a). Negative trends in projected twenty-first century precipitation in this region are mitigated somewhat by starting from the relatively wet initial state provided by late twentieth century observations. The scenarios constructed using (1) make it clear that projected precipitation trends on the regional scale are tiny, relative to interannual and decadal variability, compared to the temperature trends.

As in any effort to regionalize a climate change projection, the quality of the results is strongly constrained by uncertainties in the large-scale climate change simulation that is modified by the downscaling. A comprehensive error assessment is beyond the scope of this study, but it is obvious that the particular quantitative results presented here would be different if another choice of emissions scenario had been made. And we should anticipate that future global climate model simulations could generate different results for the same greenhouse gas scenario.

The temperature changes in the A1B-forced ensemble are very closely approximated by a linear trend, as seen in the examples shown in Figs. 1 and 2, justifying the linear approximation in term T. The CO<sub>2</sub> changes associated with the A1B scenario are rather linear too (IPCC 2007a). Additional research would be needed using the results of other greenhouse gas scenarios to explore how strongly nonlinear the continental temperature signal becomes in response to increasingly nonlinear greenhouse gas forcing.

Repetition of observed interannual variability in (1) via term A assumes stationarity of interannual and decadal variance. Other studies suggest that this assumption is likely to underestimate variability in a warmer climate (IPCC 2007a), so the variability expressed in Figs. 1b, d and 2b, d may err conservatively. Hence this property of the scenario may be inappropriate if the twentieth century climate does not sample a sufficiently broad range of interannual variability, or if very large changes in variance



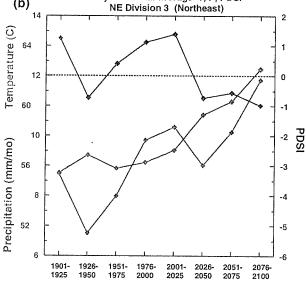


Fig. 10 Time series of 25-year annual average temperature (red), precipitation (blue) and PDSI (purple), derived from values in Figs. 1, 2, 4 and 5. The horizontal dashed lines represent a value of zero for PDSI. a NM2, as in Figs. 1b, d and 4. b NE3, as in Figs. 2b, d and 5

and extreme events occur. We speculate that the sampling issue might be a more significant concern for smaller scale downscaling, e.g. to individual catchment scales, than it is for the Climate Division scale examined here. All of these issues are ripe topics for more detailed investigation.

The repetition of pronounced climate anomalies from the twentieth century (for example, the 1930s Dust Bowl drought in the Midwest, seen in Fig. 2b, d as a multi-year anomaly of elevated temperature and depressed precipitation) provides a useful benchmark for comparative examination of well-studied twentieth century climate disasters in the context of projected climate change, as we described in Sect. 3. As is the case for the Delta method, the prescribed repetition of anomalies conserves the spatial covariability of observed short-term climate anomalies, thus providing realistic (in the sense of previously observed) patterns of climate anomalies such as droughts, perhaps better than individual climate model simulations can provide.

The increased tendency for surface water deficits in the western US as climate warms has been noted in multiple previous papers (e.g. Seager et al. 2007; Hoerling and Eischeid 2007, who focused exclusively on this issue). The drought statistics described in Sect. 3 certainly confirm the model-simulated projection of drier conditions in the western US as climate warms. The results presented here emphasize the impact of climate change on recoveryspecifically, the lack of recovery-from large twenty-first century droughts. Paleoclimate records indicate that the Southwest has been prone to episodic severe droughts for millennia (D'Arrigo and Jacoby 1991; Meko et al. 1995; Woodhouse and Overpeck 1998; Cook et al. 2004). However the projected anthropogenic temperature increase will inhibit the natural recoveries from severe droughts as exhibited in previous centuries. Warmer temperature may already be exacerbating droughts in the early twenty-first century (Breshears et al. 2005; Andreadis and Lettenmaier 2006; Weiss et al. 2009). A straightforward extension of the downscaling technique described by (1) would be to adjust the timing of severe droughts in the historical data to occur at different times in the future, to examine the relative effects of severe drought at different points along the warming trend in various regions.

The results are also broadly consistent with recent model-based studies of twenty-first century drought-related projections averaged over broader regions, that all show increased tendency for drought in the western US and other subtropical and midlatitude continental regions. Wang (2005) described soil moisture drying trends, and pointed out that uncertainties in the various land surface components of CMIP3 global models represents a major limitation in quantifying the impact of projected climate trends on aridification of agricultural areas. Sheffield and Wood (2008) showed increases in twenty-first century drought extent and frequency that are more closely tied to precipitation changes than the PDSI-based results seem to be (Burke et al. 2006), and thus less detectable because projected precipitation changes are smaller compared to natural variability than the projected temperature changes (Figs. 1, 2). The PDSI represents a complementary (and cruder, relative to direct soil moisture calculations) approach to deriving surface moisture from meteorological variables. Until surface observational networks and land surface models evolve to the point at which soil moisture



uncertainties are markedly smaller—an area of very active research—it will be important to use a variety of algorithms to describe the evolution of land surface characteristics associated with projected climate change.

Some drawbacks of the PDSI as a drought index need to be reiterated. Its simplified treatment of the hydrologic system may limit the applicability of PDSI in regions with a diversity of runoff and groundwater dynamics. Regions with the greatest amount of annual snowpack can possibly be mischaracterized by this drought index. However, if snowpack decreases as would be implied by the projections of much warmer temperatures (Brown and Mote 2009) then the oversimplified treatment of snowpack and runoff implicit in the PDSI may actually become slightly less problematic, although PDSI is still not designed for snowdominated areas. On the other hand, the internal parameters in the PDSI algorithm that relate temperature and precipitation to potential evapotranspiration and surface water storage become less realistic as climate changes, so that use of the twentieth century climate as a baseline condition affects the results. This issue is discussed further in the Appendix.

Predicting the ecological effects associated with the drought projections described here is also complex and a full treatment is beyond the scope of this paper. Different ecosystems will exhibit varying responses on multiple time scales, and the effects of increasing temperature on the plant response to drought may further complicate mortality responses, as shown in studies of mortality on piñon and juniper forests in the Southwest (Swetnam and Betancourt 1998; Breshears et al. 2005; McDowell et al. 2008). High severity drought outside of the HRV, such as described in this study, could result in high mortality of many plant species and changes in the structure, location, and type of ecosystems (Allen 2007; McDowell et al. 2008).

The implications of these drought scenarios for water management and ecosystems in the western US are diverse and complex. Temperature and drought outside the HRV require new approaches to water management (Milly et al. 2008). Aggressively conservative management of surface and ground water resources has become an urgent issue in the West, for reasons that extend beyond the climate change considerations addressed in this study, including population increase and depletion of readily available ground water (Lewis 2003).

#### 5 Summary

We describe an extremely simple approach to the challenge of downscaling temperature and precipitation trends projected from an ensemble average of relatively coarse-resolution global models. The downscaled scenario integrates

historical data from US Climate Divisions to generate a repetition of twentieth century interannual variability for the final 93 years of the twenty-first century. The repetition of historical interannual variability preserves realistic spatial covariance of such variability but imposes an artificial (and probably inappropriately conservative) constraint of no change in the amplitude of interannual variability. More sophisticated downscaling approaches in years to come can use this simple approach as a benchmark, comparing the effects of more advanced algorithms to the results of the assumptions imposed here. The general trends in temperature and precipitation shown in the scenario presented here have been discussed extensively already (e.g. in IPCC 2007a). By placing these trends into the context of observed interannual and decadal variability we draw the following general conclusions.

Temperature changes associated with the projected trends (e.g. Figs. 1a, 2a) are much greater relative to interannual variability than the corresponding precipitation trends (Figs. 1c, 2c). The summer temperature trend in particular stands out from interannual variability exhibited in the twentieth century record, such that late twenty-first century summer temperatures exceed any monthly temperatures ever recorded in parts of the Southwest. Temperature presents a much larger and more significant signal than precipitation in the A1B-forced 18-model average.

Palmer drought severity index scenarios are derived as a proxy for surface water budget changes in the twenty-first century. As has been discussed in previous studies, we find sharp increases in the severity and duration of twenty-first century drought (defined in terms of a twentieth century baseline), and the spatial scale of future droughts expands to cover much of the West. Furthermore, we find that twenty-first century droughts are driven by temperature to a greater degree than historical droughts. Recovery from historically precipitation-driven drought, repeated in these scenarios in the twenty-first century, is inhibited by the increased evaporation implied by warmer temperature in the climate change scenario developed here. We conclude that recovery from multi-year precipitation deficits, such as those that have occurred intermittently during the past millennium, and are likely to reoccur in some form in the current century, will be much more difficult in the warmer projected climate.

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these data to Climate Divisions. Code for the palmer drought severity index is available online from the NOAA National Climatic Data Center. Comments and suggestions from G. Garfin, A. Rango, Q. Xiaowei, and two anonymous reviewers are gratefully acknowledged.

### Appendix: Sensitivity studies of PDSI calculations

The algorithm used to calculate of the palmer drought severity index follows the US operational practice (Guttman 1998) derived from monthly temperature and precipitation. Several local, tunable parameters are embedded in the code describing boundary values that determine the persistence of the surface water budget from month to month. In a nonstationary climate, these boundary values may change significantly.

We examined the sensitivity of the projected PDSI values to two internal parameters. First, the soil moisture constant *wcbot*, which represents the soil moisture capacity in each Climate Division, was varied. The nationwide standard deviation of *wcbot* is 1.28 in NCDC's formulation. We repeated twenty-first century calculations after artificially inflating or deflating wcbot by one unit, and found little difference in the resulting PDSI values. We conclude that any changes to this parameter in the twenty-first century would have to be unusually large to significantly affect the results of this study.

Second, we adjusted the period of record used to define the surface water budget that is climatologically appropriate for existing conditions (CAFEC). Although the calibration period for PDSI calculations is usually the entire period of the record, this need not be the case (Heim 2002) and may not be desirable in a nonstationary climate. The projected climate change used in this study is characterized by a continuously shifting definition of "normal" conditions so it is difficult to determine the most appropriate calibration period to use for the twenty-first century. As Lockwood (1999) and Burke et al. (2006) have pointed out, the calibration period determines the relationship between temperature and evapotranspiration that is implicit in the PDSI calculation used operationally (and in the calculations presented here), leading to probable overestimates in the decrease of PDSI associated with upward temperature trends.

All scenarios discussed in the body of the paper use a calibration period of 1931–1990, the same calibration period used by NCDC for ongoing operational drought monitoring. An additional scenario was generated for New Mexico using a calibration period of 2001–2100. This scenario demonstrated patterns similar to those of the scenario illustrated in Figs. 4, 6, 7, 8, 9 and 10. However in this case 11-year PDSI running averages from 2001 to 2045 were higher (more positive) than the analogous running averages for both the twentieth century and the

1931–1990-calibrated scenario. These observed increases in PDSI during the first half of the twenty-first century reflect artificial elevation of surface water availability as the result of normalizing increased drought severity in the twenty-first century and do not make statistical sense in the near term when juxtaposed with the twentieth century PDSI records.

Nevertheless, post-2052 running averages of PDSI using twenty-first century calibration were still lower than the corresponding post-1952 twentieth century running averages, indicating that even if "normal climate" is based on twenty-first-century projections, then the western US exhibits increased drought severity, frequency, and duration (as depicted by PDSI). However, these running averages are, by construction, less negative than those shown in Figs. 4, 6, 7, 8, 9 and 10, indicating that if 2001–2100 calibration is used, the resulting drought scenario is of intermediate severity between conditions of the twentieth century and those prominent in the future scenario based on a 1931–1990 calibration.

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## Predicting future threats to the long-term survival of Gila trout using a high-resolution simulation of climate change

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Abstract Regional climates are a major factor in determining the distribution of many species. Anthropogenic inputs of greenhouse gases into the atmosphere have been predicted to cause rapid climatic changes in the next 50-100 years. Species such as the Gila trout (Oncorhynchus gilae) that have small ranges, limited dispersal capabilities, and narrow physiological tolerances will become increasingly susceptible to extinction as their climate envelope changes. This study uses a regional climate change simulation (Leung et al., Clim Change 62:75-113, 2004) to determine changes in the climate envelope for Gila trout, which is sensitive to maximum temperature, associated with a plausible scenario for greenhouse gas increases. These regional climate changes are downscaled to derive surface temperature lapse rates using regression models. This procedure indicates that suitable, warm season habitat for Gila trout will be reduced by 70% by decreasing the size of their climate envelope. Warmer temperatures coupled with a decrease in summer precipitation would also tend to increase the intensity and frequency of forest fires that are a major threat to their survival. The climate envelope approach utilized here could be used to assess climate change threats to other rare species with limited ranges and dispersal capabilities.

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### 1 Introduction

Drastic changes in climate have had profound consequences on the biota that inhabit the planet (Rees 2002). The most recent such large-scale climatic change was approximately 10,000 years ago at the end of the Pleistocene, marking the end of the last major glaciation and the beginning of the current period known as the Holocene. Earth may now be undergoing another major climatic change, toward warmer conditions, as a result of anthropogenic input of greenhouse gases (GHG) into the atmosphere from the burning of fossil fuels (IPCC 2007).

Global warming has already been detected (IPCC 2007), but major controversy remains concerning the local magnitudes and rates of change that may occur over the next century as a result of increased atmospheric GHG (Shackley et al. 1998; Khandekar et al. 2005). The evolution of 21st Century GHG forcing is not known, and climate models produce varying results from similar GHG forcing due to uncertainties associated with complex physical processes and feedback effects. Regional and local scale climate changes, and associated hydrologic changes at the watershed scale, are particularly difficult to predict. High resolution models, embedded within coarser global atmospheric models, provide the principal means for assessing the effects of future climate changes at the watershed scale.

Ecologists often use climate model simulations to make predictions about the effect of climate change on Earth's biota (Carpenter et al. 1992; Hogg and Williams 1996; Davis et al. 1998; Hill et al. 1999; Peterson et al. 2002; Mohseni et al. 2003; Schmitz et al. 2003). One common method used to predict the change in distribution of a single species is the 'climate envelope' approach. This method maps the current distribution of a species according to its climate envelope, defined as the region where a species can occur based on its observed physiological tolerances. Then, as that envelope shifts as climate changes, the species distribution is shifted to match the new envelope (Scott and Poynter 1991; Davis et al. 1998). Previous studies (Keleher and Rahel 1996; Rahel and Nibbenlink 1999; Jager et al. 1999; Cooney et al. 2005; Goosef et al. 2005; Preston 2006) have used the climate envelope approach to predict changes in distributions of Salmonids and other cold-water fish to warming scenarios.

The utility of the climate envelope approach for a single species may be limited. For example, Davis et al. (1998) demonstrated that species distribution can be affected by numerous direct and indirect interactions existing among the biota in a community. Furthermore, the range of many species may be fragmented into separate, smaller populations across a heterogeneous landscape (Levins 1969; Hanski and Gilpin 1997). Ideally, dispersal capabilities and complex interactions within a community should be considered when modeling the shifts in ranges (Davis et al. 1998; Lawton 2000).

Despite these limitations, the climate envelope approach has been successfully applied to range shifts of organisms such as higher plants and birds (Bakkenes et al. 2002; Erasmus et al. 2002). The climate envelope method is best suited to predicting changes in the distribution of species with limited ranges and dispersal capabilities. For example, Wilson et al. (2005) demonstrated that 16 species of butterflies have shifted their elevational distribution as a result of warmer temperatures, resulting in a 33% loss of habitat for those species.

For this study, we use a high resolution simulation of climate change to assess future threats to the long-term survival of the Gila trout (*Oncorhynchus gilae*, Family



Salmonidae), a federally threatened species with very limited range, physiological tolerances, and dispersal capabilities. Their extremely limited range requires a greater degree of downscaling than even the regional model provides. We therefore introduce a regression model within the climate model's computational domain in order to quantify the reduction in Gila trout habitat associated with the simulated climate change.

#### 2 Materials and methods

### 2.1 Natural history of Gila trout

Cold-water trout species (Salmonids) are well suited for modeling range shifts using the climate envelope approach. Salmonids as a group are in decline worldwide (Young and Harig 2001). Many species of trout have specialized habitat requirements and narrow physiological tolerances, requiring clear, cold, pristine waters where they feed on aquatic invertebrates (Meisner 1990; Keleher and Rahel 1996). Temperature is also very important to fish, affecting their feeding and growth rates. Near the upper and lower limits of their physiological tolerances, growth rates are reduced and they become physiologically stressed near the upper limits (Meeuwig et al. 2004; Sloat et al. 2005).

Gila trout, like many other trout species, are cold water fish requiring high levels of dissolved oxygen and habitat heterogeneity to complete their life cycle (Behnke 1992). In laboratory experiments, Gila trout become stressed as temperatures approach 21°C and often stop feeding at temperatures above 22°C. They begin to die after 8 h at temperatures above 25°C, and as the temperature approaches 29°C they begin to experience mortality within 2 h (Behnke 1992) which is consistent with other laboratory studies of coldwater Salmonids (Rahel and Nibbenlink 1999; Dickerson and Vinyard 1999; Johnstone and Rahel 2003).

The current distribution of Gila trout is limited to ten small populations in the Gila and San Francisco River headwaters, between 1,660 m and 2,810 m in elevation (Propst and Stefferud 1997, Fig. 1). Their thermal tolerances, natural and manmade barriers, and the presence of non-native trout determine seasonal shifts in the distribution and movement of Gila trout. Historically, Gila trout move upstream in summer as water temperature rises, then migrate back downstream in winter to avoid freezing conditions that occur at higher elevations (Behnke 1992). Natural and man-made barriers prevent the upstream movement of non-native fishes and prevent the Gila trout from returning upstream if they pass the barriers. Most of their habitat is located in the Gila Wilderness Area, covering approximately 200,000 ha in the southwestern portion of New Mexico. It is the largest wilderness area in the contiguous United States.

Identified threats to the survival of Gila trout include limited population size, hybridization with non-native trout species, forest fire and loss of suitable habitat (Propst et al. 1992; Brown et al. 2001; Wares et al. 2004). Catastrophic forest fires greatly reduce ground and canopy cover. Fires caused the extirpation of six populations of Gila trout in the late 1980s and the 1990s (Brown et al. 2001). Heat from fire can directly cause mortality. Ash, debris, and siltation from post-fire runoff also increase mortality of Gila trout (Brown et al. 2001).

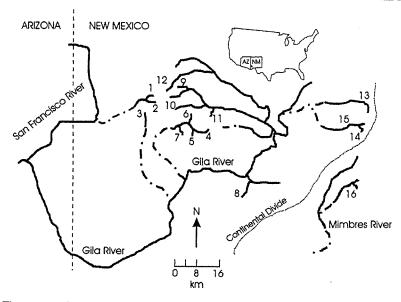


Fig. 1 The current distribution of the Gila trout in New Mexico. The *numbers on the map* indicate individual remaining populations of the Gila Trout that are confined to the upper head waters of the San Francisco and Gila Rivers. The *dashed lines* represent where the streams become intermittent, typically drying during the summer

### 2.2 The climate change simulation

For this study, potential impacts of climate change on the distribution of Gila trout were assessed using simulations from a regional model nested within a coarse resolution global model (Leung et al. 2004). The global model (the U.S. Dept. of Energy/National Center for Atmospheric Research Parallel Climate Model) was forced by increasing GHG for the entire 21st Century. Future GHG and atmospheric aerosol changes were derived from a "Business As Usual" scenario in which atmospheric CO<sub>2</sub> reaches a concentration of about 710 ppm by the end of the 21st Century (Dai et al. 2004). Two subperiods were selected for high resolution simulations by Leung et al. (2004) using the Penn State/NCAR MM5 regional model over a domain that covered the western United States. The first simulation uses GHG concentrations for the period 1996–2014. This simulation is designed to reproduce current and near-term climate conditions. The second simulation differs from the first only in its changed concentrations of GHGs and aerosols, representing projected climatic conditions for the period 2040–2059.

The focus of this study is warm season conditions in the restricted habitat region of the Gila trout. For this purpose, temperature and precipitation time series from four 40-km² MM5 grid cells closest to the trout's current habitat were selected for study. Daily precipitation values during the summer season (defined here as the 3 month period July 1–September 30) were examined. The four grid cells were also used to determine differences in mean July air temperatures. Adjacent grid cells and elevations were used to build a regression model to predict changes in temperature



with elevation. Assuming that the Gila trout has physiological characteristics similar to other Salmonids, the lower limit of their distribution in the summer will be determined by mean July air temperature of approximately 22°C, and 25°C (Keleher and Rahel 1996). During this time, their populations will be the most spatially restricted and susceptible to stochastic events. Winter precipitation and temperature were also examined because the base flow of many mountain streams is determined by cold season precipitation.

The 22°C and 25°C temperature thresholds were selected because they exceed the physiological tolerances of Salmonids in laboratory conditions and distributional limits in the wild (Keleher and Rahel 1996; Dickerson and Vinyard 1999; Sloat et al. 2005). Air temperature is often cited as a major factor in determining surface water temperatures and distributions of cold water species (Shuter and Post 1990; Dunham et al. 2003; Morrill et al. 2005). Keleher and Rahel (1996) used mean average July air temperature less than 22°C to successfully predict current geographical ranges of Salmonids in the Rocky Mountains. The average lower elevation for Gila trout determined by Propst and Stefferud (1997) was 2,125 m (±239), corresponding to a mean average July air temperature of 21.9°C (±1.6), very similar to the temperature threshold established by Keleher and Rahel (1996).

The relationship between surface water and air temperatures is nonlinear, best described with an S-shaped curve, so that the temperature of surface water increases less than air temperature in hot conditions (Mohseni et al. 2003; Morrill et al. 2005). Previous studies by Morrill et al. (2005) indicate an approximate linear increase of 0.6–0.8°C in temperature is observed with a 1°C change in weekly averages in air temperature until approximately 25°C, which also corresponds to the upper physiological limit of Gila trout. At temperatures above 25°C, the relationship flattens out as a result of increased evaporative cooling (Mohseni et al. 2003). Although the studies relating air temperature to surface water temperature do not indicate a linear relationship, empirical observations of mean air temperature during the warmest months have successfully predicted the lower elevation of several species and races of coldwater Salmonids (Keleher and Rahel 1996; Rahel and Nibbenlink 1999). Therefore, for this study we also assume that a direct relationship between mean July air temperature and the distribution will also apply to Gila trout.

Some potentially important indirect effects of temperature and precipitation change are not simulated by the climate model, and can only be inferred. Higher temperatures are associated with lower humidity and increased drought conditions that are conducive to increased fire intensity. Flow reduction associated with lower precipitation, especially in the higher altitudes, could limit the trout's ability to migrate to cooler temperatures to avoid thermal stress during the summer.

### 2.3 Determining habitat loss

To determine the habitat loss based on predicted changes in mean July surface air temperature, the United States Geological Survey (USGS) National Map and 7.5 min quadrangle maps were used to calculate changes in stream length based on changes in elevation. Changes for each stream were calculated based on the elevation for the mean July air temperature for 22°C (denoted  $Z_{22}$ ) and 25°C (denoted  $Z_{25}$ ).



### 3 Results

### 3.1 Changes in precipitation

The model simulates average Jul–Sep monsoonal precipitation of 51 mm ( $\pm 30$ ) for years 1995–2015 (Fig. 2). The corresponding 3-month average precipitation (for years 1982–2005) at the Silver Creek Divide snotel site (2,740 m) is 32.8 mm, somewhat less than the area-averaged model result. (Silver Creek Divide is the only instrumented high-elevation site in this region.) For the period 2040–2059, the model predicts summer average rainfall of 40 mm ( $\pm 20$ ), approximately 20% less than the 1996–2014 simulation. Using a one-tailed, paired t-test, the precipitation difference between the two summer time periods is marginally significant (P = 0.06).

For winter (Nov-Mar) precipitation, the model simulates 276 mm ( $\pm$ 48) for years 1996–2015. For the period 2040–2060, the model predicts, 257 mm ( $\pm$ 32), which is approximately 7% less than the 1995–2015 simulation. The model predicts somewhat less interannual variability in mid-century than is currently observed, although the statistical significance of the difference in interannual variance is questionable.

### 3.2 Changes in surface air temperature

Average, 24-h surface air temperatures in July (Fig. 3) are predicted to increase from 23.8°C ( $\pm 1.6$ ) to 25.7°C ( $\pm 1.6$ ) which is significantly different (P=0.0049). Daytime maximum temperatures are predicted to increase from 32.6°C ( $\pm 5.43$ ) to

Fig. 2 The predicted, Jul–Sep average warm season precipitation (mm) for the current time period (1996–2014) and mid century (2040–2059). Error bars represent one standard deviation. There is a marginally significant (P=0.06) decrease in total summer precipitation for the two time periods. Predicted precipitation was extracted from four 40 km<sup>2</sup> grid cells in the Gila Wilderness

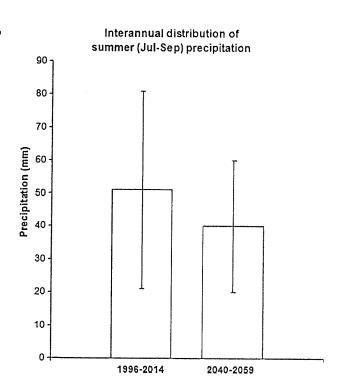
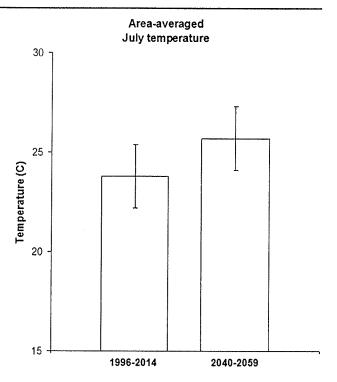




Fig. 3 The predicted change in mean daily air temperature for July, the warmest month of the year. Predicted temperatures were extracted from four 40 km<sup>2</sup> grid cells in the Gila Wilderness. There is an approximate  $1.9^{\circ}$ C increase in the future simulation which is a significant increase from the control simulation (P = 0.0049)



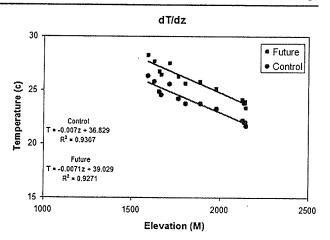
35.1°C ( $\pm$ 5.28) and nighttime minima are predicted to increase from 11.8°C ( $\pm$ 2.93) to 12.9°C ( $\pm$ 2.93). The number of days predicted to be above 37°C more than doubles from 23 days ( $\pm$ 11.7) in the current climate to 47 days ( $\pm$ 13.5) by mid century. In order to interpret these temperature changes in terms of reduction in Gila trout habitat, the surrounding 12 grid cells were used to determine the relationship between elevation and temperature in these simulations. Average elevations for the grid cells ranged from 1,594 m to 2,145 m. The average surface air temperature lapse rate based on yearly averages was 7.1°C/km ( $R^2 = 0.969$ , T = -0.0071z + 24.8). The slope of this regression line is very similar to the environmental lapse rate of 7.2°C/km in Wyoming based on empirical observations (Keleher and Rahel 1996).

A regression using mean July air temperatures was used to further refine the model to predict  $Z_{22}$  and  $Z_{25}$  respectively (Fig. 4). Based on the control simulation for 1995–2015, T=-0.0071z+36.8 ( $R^2=0.93$ ). The elevation corresponding to mean July temperature of 22°C is 2,114 m, which is within 16 m of the average lower elevation reported for Gila Trout (Propst and Stefferud 1997). The corresponding elevation associated with 25°C is 1,686 m. This value of  $Z_{25}$  is within 30 m of the lowest reported elevation of Gila trout. Using the simulations for 2040–2059, the regression model was T=-0.0072z+39.0,  $R^2=0.927$ . The lapse rate does not change appreciably in the simulated future climate, but  $Z_{22}$  and  $Z_{25}$  are raised to 2,394 m and 1,972 m respectively. Between the control and future simulations, a change in elevation of 269 and 286 m is predicted for  $Z_{22}$  and  $Z_{25}$  respectively.

To determine habitat loss, the shift in elevation based on  $Z_{22}$  and  $Z_{25}$  were both used. A change in 286 m represents a 25% loss in elevational habitat available to Gila trout based on the lowest recorded elevation. Actual stream loss for  $Z_{25}$  is



Fig. 4 Regression models used to predict the environmental lapse rate in July. Lower elevational limits of Gila trout are predicted for control, 1995–2014 and future simulations 2040–2059 using the mean air temperature of 22°C and 25°C



approximately 7.3 km or 6% of the total stream habitat available. However, this would mean a complete loss of two trout streams (Table 1). A 61% loss in elevational habitat was predicted for  $Z_{22}$ . The actual stream loss for  $Z_{22}$  was approximately 82.9 km of a total of 118.7 km of inhabited stream reaches reported by Propst and Stefferud (1997), which includes five streams in addition to the streams listed in the 2003 US Fish and Wildlife Recovery Plan (Table 1). This is a 70% loss in habitable stream length and a total loss of three streams which are in listed in the

Table 1 Current occupied stream length with elevational distributions for Gila trout

Stream	Drainage	Length (km)	Elevation upper/lower	Current	Predicted loss (km)	
				Temp °C	$\overline{Z_{22}}$	$Z_{25}$
Spruce Creek	San Francisco	3.7	2,500/2,055	22.4	2.9	0
Big Dry Creek	San Francisco	1.9	2,555/2,365	20.74	0.34	0
Sacaton Creekb	Gila River	1.6	2,279/2,084	22.2	1.6 <sup>a</sup>	0
Mogollon	Gila River	28.8	2,255/2,036	22.6	28.8 <sup>a</sup>	0
Trail Creek <sup>b</sup>	Gila River	1.8	2,121/2,036	22.6	1.8a	0
Sheep Corral	Gila	1.3	1,740/1,660	25.2	1.3a	1.3a
White Creek <sup>b</sup>	Gila River	14.2	2,255/2,036	22.6	14.2 <sup>a</sup>	0
McKenna Creekb	Gila River	1.2	2,110/2,015	22.7	1.2a	0
Iron Creek <sup>b</sup>	Gila River	4.3	2,810/2,675	18.1	4.3 <sup>a</sup>	0
Main Diamond	East Fork	6.1	2,675/2,320	20.6	0.8	0
South Diamond	East Fork	6.7	2,560/2,365	20.3	1.2	0
McKnight	Mimbres	8.5	2,510/2,100	22.1	6.2	0
Black Canyon	East Fork	18.2	2,734/2,058	22.4	14.3	0
Lower Little Creek	West Fork	6.0	1,960/1,850	23.9	$6.0^{\mathrm{a}}$	6.0a
Upper White Creek	West Fork	8.8	2,805/2,250	21.2	2.6	0

The column for current temperature was calculated using the predicted environmental lapse rate for mean July air temperature for the control simulation (1995–2014). Predicted loss of habitat was based on the changes in elevation corresponding to the predicted temperature increases of 1.9°C ( $Z_{22}=2,398 \, \mathrm{m}, \, Z_{25}=1,976 \, \mathrm{m}$  for the future simulation)

<sup>&</sup>lt;sup>b</sup>Gila trout streams not in the US Fish and Wildlife recovery plan



<sup>&</sup>lt;sup>a</sup>Total loss of stream habitat

USFWS recovery plan (2003) and all five additional streams listed by Propst and Stefferud (1997).

#### 4 Discussion

The regional climate model predicts a 20% decrease summer precipitation, a nearly 2°C increase in summertime average air temperature, and a pronounced increase in the number of days above 32°C and 37°C, by mid century (years 2040–2059) in the region inhabited by Gila trout. The combination of precipitation and temperature change in this simulation would have a profound long-term impact on the Gila trout. Assuming the strong relationship between weekly air temperature and surface water temperature, the increase in average summertime temperatures and the number of days above 37°C will increase thermal loading in the water, limiting the movement of the Gila Trout to lower altitudes during the summer season. Gila trout populations are currently limited to 1,660 m and 2,810 m in elevation depending on the drainage they inhabit (Propst and Stefferud 1997). Our calculations indicate that a 2°C change in average seasonal air temperatures may cause an elevational range shift of approximately 269 m to 286 m. This could represent a 70% loss in suitable habitat for existing trout streams in July based on changes in elevation.

The control simulation for the current climate accurately predicted that the lowest elevation for Gila trout would be 1,686 m based on a thermal tolerance of 25°C, and predicted the average low elevation based on mean July surface air temperature of 22°C. This corresponds well with other published reports for cold water Salmonids and laboratory studies (Behnke 1992; Keleher and Rahel 1996; Rahel and Nibbenlink 1999). Gila trout habitat is located at a lower latitude than many other trout species so Gila trout may be better acclimated to slightly warmer temperatures, as shown by laboratory studies on races of cutthroat trout that inhabit wide geographic regions (Wagner et al. 2001). Our results are qualitatively similar to other predictions that global warming will reduce suitable habitat for cold water species (Keleher and Rahel 1996; Jager et al. 1999; Mohseni et al. 2003).

We have extended previous modeling studies predicting change at the regional scale by deriving a regression model for the lapse rate of surface air temperature to quantify changes at the catchment scale. We do not empirically demonstrate changes in stream flow based on air temperatures, but the close agreement between our regression results and the current elevational limit of Gila trout based on reported thermal limits helps validate the approach.

Gila trout are capable of long-distance dispersal to many habitats, especially during the cooler months. However, in some streams, dispersal is limited and the lower elevational limit is not realized due to natural and man-made barriers that prevent the upstream movement of non-native trout species. During the summer, they most likely move to colder waters at higher elevations. At this time, the amount of suitable habitat for Gila trout will be at its smallest extent and the populations will be most susceptible to extirpations due to stochastic events (Lande 1993).

Decreases in summer precipitation, which are less pronounced and less certain than the temperature changes, would reduce stream flow. In addition, base flow could decrease as a result of diminished snow pack and earlier snowmelt runoff associated with warmer winter temperatures (as described by Hurd and Coonrod 2007, in a



recent study of the nearby Rio Grande). If the headwater streams that currently act as warm season refugia for the trout become greatly reduced or ephemeral, then the Gila trout would become stressed or suffer higher mortality as they are limited to sub-optimal habitat in warmer waters downstream. More detailed examination of the effects of climate change on snow pack and stream flows in the Gila Wilderness is beyond the scope of this study but deserves additional analysis.

A decrease in suitable Gila trout habitat as a result of the predicted scenario would lead to further declines in populations and increased risk to environmental and demographic stochastic events (Lande 1993). For example, decreased precipitation and a longer warmer season would increase the fire potential, both in frequency or severity. Thus, even if local climate change does not directly cause of the demise of Gila trout, indirect effects and stochastic events could be equally important.

Quantitative climate change predictions are dependent on the particular model and forcing scenario chosen, and do not account for climate forcings other than GHG and aerosols, so any prediction is subject to very high levels of uncertainty. However the changes described here are qualitatively similar to many other large-scale simulations of climate change at high elevation in the interior of North America (IPCC 2007; NAST 2001). For example, similar to the climate scenarios we used, the most recent IPCC report (Christensen et al. 2007) summarized that the southwest will likely experience larger warming during summer, especially for maximum summer temperatures, and annual precipitation will likely decrease. With regard to temperature changes, moreover, a strong scientific consensus now exists suggesting that the principal uncertainty in the predictions described here is simply timing: different scenarios and models would yield similar warming either somewhat sooner or somewhat later than the 2040–2059 period simulated here (IPCC 2007).

A more sophisticated assessment of future trends in Gila trout habitat would require a coupled watershed-scale hydrologic model that explicitly simulates stream flow, water temperature, and perhaps even water quality, in association with climate change. For example, Leung et al. (1996), Leung and Wigmosta (1999) used a one-way coupled regional climate and watershed model to study climate change effects on snow pack and stream flow. Their watershed model has been extended to simulate stream temperature as well. Such an assessment is well beyond the scope of the present study, but we advocate the further development and use of coupled atmosphere-land-hydrology models that are capable of carrying out simulations of such scope and scale.

There are also many non-climatic factors that affect a species range within its climate envelope. However, the combination of small population size, restricted range, limited dispersal capabilities, and narrow physiological tolerances, greatly increases the susceptibility of the Gila trout to extinction through environmental and demographic stochasticity. The use of climate models to predict changes in the climate envelope of these sensitive species will aid in predicting future threats such as loss of suitable habitat to species with limited dispersal capabilities and narrow physiological tolerances. To foster the long-term survival of the Gila trout and other, similar aquatic species, long term monitoring projects should be developed and implemented, especially at high elevations. The need to determine temperature changes and thermal loading in headwater streams is crucial, but these changes occur on spatial scales that are smaller than the resolution of most global climate change simulations. Better estimation of base flow rates, based on seasonally varying



precipitation rates (and other variables not considered here) are also important. Long-term data collection and climate monitoring efforts will be valuable assets for validating current models and promoting the development of long-term species management plans.

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# AAAS Board Statement on Climate Change

Approved by the Board of Directors American Association for the Advancement of Science 9 December 2006

The scientific evidence is clear: global climate change caused by human activities is occurring now, and it is a growing threat to society. Accumulating data from across the globe reveal a wide array of effects: rapidly melting glaciers, destabilization of major ice sheets, increases in extreme weather, rising sea level, shifts in species ranges, and more. The pace of change and the evidence of harm have increased markedly over the last five years. The time to control greenhouse gas emissions is now.

The atmospheric concentration of carbon dioxide, a critical greenhouse gas, is higher than it has been for at least 650,000 years. The average temperature of the Earth is heading for levels not experienced for millions of years. Scientific predictions of the impacts of increasing atmospheric concentrations of greenhouse gases from fossil fuels and deforestation match observed changes. As expected, intensification of droughts, heat waves, floods, wildfires, and severe storms is occur-

ring, with a mounting toll on vulnerable ecosystems and societies. These events are early warning signs of even more devastating damage to come, some of which will be irreversible.

Delaying action to address climate change will increase the environmental and societal consequences as well as the costs. The longer we wait to tackle climate change, the harder and more expensive the task will be.

History provides many examples of society confronting grave threats by mobilizing knowledge and promoting innovation. We need an aggressive research, development and deployment effort to transform the existing and future energy systems of the world away from technologies that emit greenhouse gases. Developing clean energy technologies will provide economic opportunities and ensure future energy supplies.

In addition to rapidly reducing greenhouse gas emissions, it is essential that we develop strategies to adapt to ongoing changes and make communities more resilient to future changes. The growing torrent of information presents a clear message: we are already experiencing global climate change. It is time to muster the political will for concerted action. Stronger leadership at all levels is needed. The time is now. We must rise to the challenge. We owe this to future generations.

The conclusions in this statement reflect the scientific consensus represented by, for example, the Intergovernmental Panel on Climate Change (www.ipcc.ch/), and the Joint National Academies' statement (http://nationalacademies.org/onpi/o6072005.pdf).

For more information: www.aaas.org/climate



### AAAS Board Statement on Climate Change

Approved by the AAAS Board of Directors 9 December 2006

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http://www.aaas.org//news/releases/2009/1204climate\_statement.shtml

**News: News Archives** 

### AAAS Reaffirms Statements on Climate Change and Integrity

The American Association for the Advancement of Science (AAAS) has reaffirmed the position of its Board of Directors and the leaders of 18 respected organizations, who concluded based on multiple lines of scientific evidence that global climate change caused by human activities is now underway, and it is a growing threat to society.

"The vast preponderance of evidence, based on years of research conducted by a wide array of different investigators at many institutions, clearly indicates that global climate change is real, it is caused largely by human activities, and the need to take action is urgent," said Alan I. Leshner, chief executive officer of AAAS and executive publisher of the journal *Science*.

AAAS expressed grave concerns that the illegal release of private emails stolen from the University of East Anglia should not cause policy-makers and the public to become confused about the scientific basis of global climate change. Scientific integrity demands robust, independent peer review, however, and AAAS therefore emphasized that investigations are appropriate whenever significant questions are raised regarding the transparency and rigor of the scientific method, the peer-review process, or the responsibility of individual scientists. The responsible institutions are mounting such investigations.

AAAS is not itself an investigative body, Leshner emphasized, but the Association will carefully evaluate the conclusions of appropriate authorities who have been asked to review the emails. Selectively publicized language in messages exchanged over a number of years among several scientists has been interpreted by some to suggest unethical actions such as data manipulation or suppression.

"AAAS takes issues of scientific integrity very seriously," Leshner said. "It is fair and appropriate to pursue answers to any allegations of impropriety. It's important to remember, though, that the reality of climate change is based on a century of robust and well-validated science."

The AAAS Board of Directors asserted in a <u>statement</u> issued 9 December 2006 that "the scientific evidence is clear: global climate change caused by human activities is occurring now, and it is a growing threat to society." Clear evidence of climate change is based upon "accumulating data from across the globe" that reveals "a wide array of effects: rapidly melting glaciers, increases in extreme weather, rising sea levels, shifts in species ranges, and more," the AAAS Board reported. Reliable sensor data show an upturn in average temperatures for at least the past 30 years.

The AAAS Board noted that "the pace of change and the evidence of harm have increased markedly over the last five years. The time to control greenhouse gas emissions is now."

AAAS joined the leaders of 17 other leading organizations in signing a <u>letter</u> sent 21 October 2009 to the U.S. Senate, emphasizing based upon rigorous research that human-induced climate change is ongoing and will have broad impacts on society—including the global economy and the environment.

4 December 2009

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# AMERICAN METEOROLOGICAL SOCIETY 1919

### Climate Change

An Information Statement of the American Meteorological Society (Adopted by AMS Council on 1 February 2007) *Bull. Amer. Met. Soc.*, **88** 

The following is an Information Statement intended to provide a trustworthy, objective, and scientifically up-to-date explanation of scientific issues of concern to the public at large.

### Background

This statement is consistent with the vast weight of current scientific understanding as expressed in assessments and reports from the Intergovernmental Panel on Climate Change, the U. S. National Academy of Sciences, and the U. S. Climate Change Science Program. All these reports recognize the uncertainties in climate projections, and identify the scientific work needed to reduce those uncertainties. Although the statement has been drafted in the context of concerns in the United States, the underlying issues are inherently global in nature.

This summary of the current state of scientific understanding is based on the peer-reviewed scientific literature. We are grateful to our members who contributed considerable scientific help in its preparation. A few members offered alternative views on climate change or put quite different emphases on the uncertainties of climate projections. In the last fifteen years, scientific debates of this kind have stimulated much new research which deepened considerably our understanding of climate, and reduced the uncertainties in our projections. The scientific process of debate and investigation is the lifeblood of science; this essential process must continue.

### How is climate changing?

Climate is changing in many ways. Global mean temperatures have been rising steadily over the last 40 years, with the six warmest years since 1860 occurring in the last decade. Regionally, the warming trend is greatest in northern latitudes, over land, and at night. Decreases in Arctic sea ice have been observed. Most studies indicate that ice loss has recently accelerated at the margins of Greenland and the West Antarctic ice sheet, whereas the East Antarctic ice sheet and the Greenland interior appear to be gaining mass. In the U.S. most of the observed warming has occurred in the West and in Alaska. However, there are regional variations in the signature of climate change, with warming in the western U.S. but little or no annual temperature change in the southeast U.S. in recent decades. Temperature rises have significant hydrologic effects. Freezing levels are rising in elevation, rain occurs instead of snow at mid-elevations, spring maximum snowpack is decreasing, snowmelt occurs earlier, and the spring runoff that supplies over two-thirds of the western U.S. streamflow is reduced.

Evidence for warming is also observed in seasonal changes with earlier springs, longer frost-free periods and longer growing seasons, and shifts in natural habitats and in migratory patterns of birds.

Sea levels are generally rising around the world and glaciers are generally in retreat. A component of sea level rise is attributed to expansion due to a long-term increase in ocean heat content. The impacts of even small rises in sea level on coastal zones are expected to be severe, particularly in conjunction with storm surges associated with vigorous weather systems.

### Why is climate changing?

Climate has changed throughout geological history, for many natural reasons such as changes in the sun's energy received by Earth arising from slow orbital changes, or changes in the sun's energy reaching Earth's surface due to volcanic eruptions. In recent decades, humans have increasingly affected local, regional, and global climate by altering the flows of radiative energy and water through the Earth system (resulting in changes in temperature, winds, rainfall, etc.), which comprises the atmosphere, land surface, vegetation, ocean, land ice, and sea ice. Indeed, strong observational evidence and results from modeling studies indicate that, at least over the last 50 years, human activities are a major contributor to climate change.

Direct human impact is through changes in the concentration of certain trace gases such as carbon dioxide, chlorofluorocarbons, methane, nitrous oxide, ozone, and water vapor, known collectively as greenhouse gases. Enhanced greenhouse gases have little effect on the incoming energy of the sun, but they act as a blanket to reduce the outgoing infrared radiation emitted by Earth and its atmosphere; the surface and atmosphere therefore warm so as to increase the outgoing energy until the outgoing and incoming flows of energy are equal. Carbon dioxide accounts for about half of the human-induced greenhouse gas contribution to warming since the late 1800s, with increases in the other greenhouse gases accounting for the rest; changes in solar output may have provided an augmentation to warming in the first half of the 20<sup>th</sup> century.

Carbon dioxide concentration is rising mostly as a result of fossil-fuel burning and partly from clearing of vegetation; about 50% of the enhanced emissions remain in the atmosphere, while the rest of the Earth system continues to absorb the remaining 50%. In the last 50 years atmospheric CO<sub>2</sub> concentration has been increasing at a rate much faster than any rates observed in the geological record of the past several thousand years. Global annual-mean surface temperatures are rising at a rapid rate to values higher than at any time in the last 400 (and probably in the last 1000) years. Once introduced in the atmosphere, carbon dioxide remains for at least a few hundred years and implies a lengthy guarantee of sustained future warming. Further, increases in greenhouse gases are nearly certain to produce continued increases in temperature. Such changes in temperature lead to changes in clouds, pressure, winds, and rainfall in a complex sequence of further effects.

Human activity also affects climate through changes in the number and physical properties of tiny particles (aerosols) suspended in the atmosphere, and through changes in the land surface. Aerosols arise from dust, sea salt, and air pollution. They absorb and redirect radiation emitted by the sun and Earth. They also modify the ability of clouds to reflect sunlight and to form precipitation. Most aerosols originating from human activity act to cool the planet and so partly counteract greenhouse gas effects; this effect will diminish as clean-air legislation leads to reduced emissions of fine aerosols. Stratospheric aerosols emitted by occasional large sulfur-rich volcanic eruptions can cause temporary (1–3 years) reductions in surface temperature. By contrast, carbon soot from wildfires and biomass burning warms the planet, so that decreases in soot would reduce warming. Aerosols have much shorter lifetimes in the atmosphere than most

greenhouse gases and exhibit large regional variations in concentration and properties. A deeper understanding of their global and regional roles is a high priority for climate science.

Changes in the land surface also change the surface water and energy budgets and act to redirect the incoming solar energy. Humans alter land surface characteristics through irrigation practices, removal and reintroduction of forests, agricultural changes to vegetative cover, reduction of soil water recharge by soil compaction, and modification of heat storage by cities and reservoirs. Many of these lead to changes in the reflectivity of the surface. Although net global effects are not expected to be large, such changes can have significant effects on regional and local climate patterns.

The interaction of all these effects on climate is complex. For example, decreases of stratospheric ozone have likely contributed to the recent contraction and intensification of the polar vortex around Antarctica, producing warming in the Antarctic Peninsula, the northern most peninsula that points toward South America, and cooling over Antarctica. As a further example, the east—west difference in U.S. temperature trends may be tied to the spatial patterns of global ocean warming, or to differences in aerosol distribution and effects, or to natural climate variations that affect atmospheric circulation, cloudiness, and precipitation within the nation. Accurate characterization of the influence of each of the greenhouse gases, of aerosols, of oceans and natural climate variability, and of land-surface influences, along with their combined effects, is a high priority for the climate science research community.

### How can climate change be projected in the future?

Climate will continue to change due to natural and human causes. The most comprehensive projections of future climate rely on numerical models of the climate system, of which there are many. Climate models are complex computer codes based on measurements and on fundamental physical laws of motion, thermodynamics, and radiative transfer. These are expressed in mathematical equations representing changes of winds in the atmosphere; currents in the ocean; exchanges of heat and moisture between the atmosphere and Earth's surface; the release of latent heat by condensation during the formation of clouds and raindrops; and the absorption of sunshine and emission of infrared radiation.

Climate models were developed from weather forecast models through coupling with models of the ocean, land surface and vegetation, cryosphere, etc., so as to represent the complexity of the climate system. Changes in the means and extremes of temperature and precipitation in response to increasing greenhouse gases can be projected over decades to centuries even though the timing of individual weather events cannot be projected. Unlike daily weather forecasts, there is limited historical basis of experience on which to judge the accuracy of climate projections. Confidence must be assessed by other methods. These include inferences from prehistoric paleoclimate evidence, and careful process-study observations of the causal chain between energy flow changes and climate pattern responses. A useful demonstration of the validity of current climate models is their ability to reproduce the global mean temperature changes of the 20<sup>th</sup> century when (and only when) they include all known natural and human-induced climate forcings.

Weather predictions beyond a few days are nowadays based on ensembles of simulations that estimate the range of probable outcomes. The same ensemble concept is used for projections of climate change, where uncertainty arises from the limitations of models and from the emission

scenarios used to represent the effects of human activity. Model limitations include uncertainties in the way in which processes that operate at scales smaller than the resolved scale of the model are represented, as well as those that arise from components of the Earth system not currently included in models. Among the most important uncertainties are changes in clouds, which can either cool or warm the climate. Recent satellite evidence rules out the possibility that cloud changes could offset most greenhouse warming and suggests that they might even add to it. The emission scenarios used to drive the climate model projections are uncertain since they depend on socioeconomic responses to climate change; these uncertainties have been factored into future assessments.

### How will climate change in the future?

There will be inevitable climate changes from the greenhouse gases already added to the Earth system. Their effect is delayed several decades because the thermal inertia of the oceans ensures that the warming lags behind the driving forcing. For the next several decades there is a clear consensus on projected warming rates from human influences among different models and different emission scenarios.

Many of the trends observed in recent decades are projected to continue. The model projections all show greater warming in northern polar regions, over land areas, and in the winter season, consistent with observed trends. However, considerable uncertainty still exists in the degree to which the land will warm more than the oceans, and this contributes significantly to uncertainties in future projections of global sea level rise. Nevertheless, where coastal elevations are low, small rises lead to large inland intrusions of sea water. In the coming century, these rises are expected to accelerate as the oceans absorb more heat and the melting of land ice-sheets increases. With its large mass and high capacity for heat storage, the ocean will continue to slowly warm to great depths and thus expand for several centuries. Moreover, paleoclimatic observations and ice-sheet modeling indicate that the melting of the Greenland and possibly the West Antarctic ice sheets will eventually cause global sea level to rise on the order of meters if warming continues at its present rate beyond the 21st century.

Confidence in projections is higher for temperature than other elements, such as rainfall. The atmospheric water content is likely to increase globally in line with warmer temperatures and consequently the global hydrological cycle will accelerate. However, changes in precipitation patterns will differ considerably by region and by season. In some regions, the accelerated hydrological cycle will act to reinforce existing patterns of rainfall, leading to persistent droughts and floods. In other regions, the greater warming at high latitudes and over land will change the large-scale atmospheric circulation, leading to significant regional shifts in the patterns of rainfall. For example, annual precipitation for the U.S. is projected to rise across the northern states, and decrease across the southern states.

Precipitation is expected to become more intense (i.e., precipitation rates and total precipitation in storms will increase), with implications for water resource management and flooding. Moreover, continued warming also implies a net long-term reduction of winter snow accumulations (in favor of rain), and thus a reduced spring snowpack, with consequently deficient dry-season river flows; widespread retreat of mountain glaciers will also eventually lead to reduced dry-season flows. Prolonged episodes of wet and dry conditions could both become more frequent, an outcome seemingly paradoxical but physically plausible. Drought is

projected to increase over the continental interior and particularly the southwest U.S. However, natural decadal time-scale variations in world ocean conditions can cause similar effects. Paleoclimatic observations suggest that droughts lasting decades are possible, and that these prolonged droughts could occur without warning.

Weather patterns will continue to vary from day to day and from season to season, but it is likely that the frequency of extreme weather will change. A growing body of recent scientific work suggests that hurricanes have become more intense over the last several decades. There is evidence both for and against the existence of a detectable anthropogenic signal in the tropical cyclone climate record to date. Though hurricanes are projected to intensify with further warming of sea surface temperatures, significant uncertainty remains as to how other influences on hurricane strength will change in the future. Midlatitude storm tracks are likely to shift poleward, with fewer but more intense storms.

Longer-term variations such as El Niño and La Niña will also continue to occur but the intensity and frequency of occurrence may change. Climate change should be assessed on the basis of changes over long time periods. It should not be assessed on a single unusual weather event, nor even on several years of anomalous weather. Heat waves and cold snaps, and the weather conditions giving rise to them, will continue to occur, but there will be proportionately more extreme warm periods and fewer cold periods. Projections for fewer frost days (those with minimum temperature below freezing) and longer growing seasons are consistent with observed changes in the second half of the 20<sup>th</sup> century over most areas of the U.S., particularly the West. Drier conditions in summer, such as those expected over the southern U.S. and southern Europe, will contribute to more severe episodes of extreme heat. Critical temperature thresholds above which ecosystems and crop systems (e.g., food crops such as rice and wheat) suffer increasingly severe damage are likely to be exceeded more frequently. On the other hand, longer growing seasons and CO<sub>2</sub> fertilization enhancing plant growth may potentially lead to some benefits.

Sustained global economic growth is increasing not only long-lived greenhouse gases in the atmosphere but is also leading to increases in shorter-lived species which affect both climate and air quality such as aerosols and low-level ozone. Air quality is likely to become a major issue affecting human health and life expectancy. Increasing urbanization will exacerbate the urban heat island effect and lead to a greater number of days with poor air quality. In some locations, surface ozone concentrations are projected to rise above levels considered harmful to humans, plants and other ecosystems.

The Earth system is highly interconnected and complex, with many processes and feedbacks that are just beginning to be detected and understood. The continued ability of the biosphere to take up carbon at its current rate is uncertain; the issue is whether the soil and land vegetation will become a source rather than a sink of carbon as the planet warms. The portion of increased carbon dioxide absorbed by the world ocean is making the ocean more acidic, with negative implications for shell- and skeleton-forming organisms and more generally for ocean ecosystems. There are indications that regions of permafrost, for example in Alaska, are already melting with the potential to release massive amounts of carbon into the atmosphere. Such an event has the potential to produce abrupt and catastrophic changes in climate. These processes are only now being quantified and introduced into climate models, and remain a large source of uncertainty.

### Final remarks

Despite the uncertainties noted above, there is adequate evidence from observations and interpretations of climate simulations to conclude that the atmosphere, ocean, and land surface are warming; that humans have significantly contributed to this change; and that further climate change will continue to have important impacts on human societies, on economies, on ecosystems, and on wildlife through the 21<sup>st</sup> century and beyond. Focusing on the next 30 years, convergence among emission scenarios and model results suggest strongly that increasing air temperatures will reduce snowpack, shift snowmelt timing, reduce crop production and rangeland fertility, and cause continued melting of the ice caps and sea level rise. Important goals for future work include the need to understand the relation of climate at the state and regional level to the patterns of global climate and to reverse the decline in observational networks that are so critical to accurate climate monitoring and prediction.

Policy choices in the near future will determine the extent of the impacts of climate change. Policy decisions are seldom made in a context of absolute certainty. Some continued climate change is inevitable, and the policy debate should also consider the best ways to adapt to climate change. Prudence dictates extreme care in managing our relationship with the only planet known to be capable of sustaining human life.

[This statement is considered in force until February 2012 unless superseded by a new statement issued by the AMS Council before this date.]

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### National Policy 07.1 CLIMATE CHANGE

(Adopted by Council on November 18, 2007)

Emissions of greenhouse gases from human activities are changing the atmosphere in ways that affect the Earth's climate. Greenhouse gases include carbon dioxide as well as methane, nitrous oxide and other gases. They are emitted from fossil fuel combustion and a range of industrial and agricultural processes.

The evidence is incontrovertible: Global warming is occurring. If no mitigating actions are taken, significant disruptions in the Earth's physical and ecological systems, social systems, security and human health are likely to occur. We must reduce emissions of greenhouse gases beginning now.

Because the complexity of the climate makes accurate prediction difficult, the APS urges an enhanced effort to understand the effects of human activity on the Earth's climate, and to provide the technological options for meeting the climate challenge in the near and longer terms. The APS also urges governments, universities, national laboratories and its membership to support policies and actions that will reduce the emission of greenhouse gases.

### **Climate Change Commentary**

(adopted by Council on April 18, 2010)

There is a substantial body of peer reviewed scientific research to support the technical aspects of the 2007 APS statement. The purpose of the following commentary is to provide clarification and additional details.

The first sentence of the APS statement is broadly supported by observational data, physical principles, and global climate models. Greenhouse gas emissions are changing the Earth's energy balance on a planetary scale in ways that affect the climate over long periods of time (~100 years). Historical records indicate that the Earth's climate is sensitive to energy changes, both external (the sun's radiative output, changes in Earth's orbit, etc.) and internal. Internal to our global system, it is not just the atmosphere, but also the oceans and land that are involved in the complex dynamics that result in global climate. Aerosols and particulates resulting from human and natural sources also play roles that can either offset or reinforce greenhouse gas effects. While there are factors driving the natural variability of climate (e.g., volcanoes, solar variability, oceanic oscillations), no known natural mechanisms have been proposed that explain all of the observed warming in the past century. Warming is observed in land-surface temperatures, sea-surface temperatures, and for the last 30 years, lower-atmosphere temperatures measured by satellite. The second sentence is a definition that should explicitly include water vapor. The third sentence notes various examples of human contributions to greenhouses gases. There are, of course, natural sources as well.

The evidence for global temperature rise over the last century is compelling. However, the word "incontrovertible" in the first sentence of the second paragraph of the 2007 APS statement is rarely used in science because by its very nature science questions prevailing ideas. The observational data indicate a global surface warming of 0.74 °C (+/- 0.18 °C) since the late 19th century. (Source: <a href="http://www.ncdc.noaa.gov/oa/climate/globalwarming.html">http://www.ncdc.noaa.gov/oa/climate/globalwarming.html</a>)

The second sentence in the second paragraph states that without mitigating actions significant disruptions in the Earth's physical and ecological systems, social systems, security and health are likely. Such predicted disruptions are based on direct measurements (e.g., ocean acidification, rising sea levels, etc.), on the study of past climate change phenomena, and on climate models. Climate models calculate the effects of natural and anthropogenic changes on the ecosphere, such as doubling of the CO<sub>2</sub>-equivalent [1] concentration relative to its pre-industrial value by the year 2100. These models have uncertainties associated with radiative response functions, especially clouds and water vapor. However, the models show that water vapor has a net positive feedback effect (in addition to CO<sub>2</sub> and other gases) on global temperatures. The impact of clouds is less certain because of their dual role as scatterers of incoming solar radiation and as greenhouse

contributors. The uncertainty in the net effect of human activity on climate is reflected in the broad distribution of the predicted magnitude of the consequence of doubling of the  $CO_2$ -equivalent concentration. The uncertainty in the estimates from various climate models for doubling  $CO_2$ -equivalent concentration is in the range of 1°C to 3°C with the probability distributions having long tails out to much larger temperature changes.

The last sentence in the second paragraph articulates an immediate policy action to reduce greenhouse gas emissions to deal with the possible catastrophic outcomes that could accompany large global temperature increases. Even with the uncertainties in the models, it is increasingly difficult to rule out that non-negligible increases in global temperature are a consequence of rising anthropogenic CO<sub>2</sub>. Thus given the significant risks associated with global climate change, prudent steps should be taken to reduce greenhouse gas emissions now while continuing to improve the observational data and the model predictions.

The third paragraph, first sentence, recommends an enhanced effort to understand the effects of human activity on Earth's climate. This sentence should be interpreted broadly and more specifically: an enhanced effort is needed to understand both anthropogenic processes and the natural cycles that affect the Earth's climate. Improving the scientific understanding of all climate feedbacks is critical to reducing the uncertainty in modeling the consequences of doubling the CO<sub>2</sub>-equivalent concentration. In addition, more extensive and more accurate scientific measurements are needed to test the validity of climate models to increase confidence in their projections.

With regard to the last sentence of the APS statement, the role of physicists is not just "...to support policies and actions..." but also to participate actively in the research itself. Physicists can contribute in significant ways to understanding the physical processes underlying climate and to developing technological options for addressing and mitigating climate change.

[1] The concentration of CO<sub>2</sub> that would give the same amount of radiative impact as a given mixture of CO<sub>2</sub> and other greenhouse gases (methane, nitrous oxide, etc.). The models sum the radiative effects of all trace gases and treat the total as if it comes from an "equivalent" CO<sub>2</sub> concentration. The calculation for all gases other than CO<sub>2</sub> takes into account only increments relative to their pre-industrial values, so that the pre-industrial effect for CO<sub>2</sub> and CO<sub>2</sub>-equivalent are the same.

### AGU - Earth | Oceans | Atmosphere | Space | Planets

Home » Science Policy » Position Statements » Human Impacts on Climate

### AGU Position Statement

Human Impacts on Climate Adopted by Council December 2003 Revised and Reaffirmed December 2007

The Earth's climate is now clearly out of balance and is warming. Many components of the climate system—including the temperatures of the atmosphere, land and ocean, the extent of sea ice and mountain glaciers, the sea level, the distribution of precipitation, and the length of seasons—are now changing at rates and in patterns that are not natural and are best explained by the increased atmospheric abundances of greenhouse gases and aerosols generated by human activity during the 20th century. Global average surface temperatures increased on average by about 0.6°C over the period 1956–2006. As of 2006, eleven of the previous twelve years were warmer than any others since 1850. The observed rapid retreat of Arctic sea ice is expected to continue and lead to the disappearance of summertime ice within this century. Evidence from most oceans and all continents except Antarctica shows warming attributable to human activities. Recent changes in many physical and biological systems are linked with this regional climate change. A sustained research effort, involving many AGU members and summarized in the 2007 assessments of the Intergovernmental Panel on Climate Change, continues to improve our scientific understanding of the climate.

During recent millennia of relatively stable climate, civilization became established and populations have grown rapidly. In the next 50 years, even the lower limit of impending climate change—an additional global mean warming of 1°C above the last decade—is far beyond the range of climate variability experienced during the past thousand years and poses global problems in planning for and adapting to it. Warming greater than 2°C above 19th century levels is projected to be disruptive, reducing global agricultural productivity, causing widespread loss of biodiversity, and—if sustained over centuries—melting much of the Greenland ice sheet with ensuing rise in sea level of several meters. If this 2°C warming is to be avoided, then our net annual emissions of CO<sub>2</sub> must be reduced by more than 50 percent within this century. With such projections, there are many sources of scientific uncertainty, but none are known that could make the impact of climate change inconsequential. Given the uncertainty in climate projections, there can be surprises that may cause more dramatic disruptions than anticipated from the most probable model projections.

With climate change, as with ozone depletion, the human footprint on Earth is apparent. The cause of disruptive climate change, unlike ozone depletion, is tied to energy use and runs through modern society. Solutions will necessarily involve all aspects of society. Mitigation strategies and adaptation responses will call for collaborations across science, technology, industry, and government. Members of the AGU, as part of the scientific community, collectively have special responsibilities: to pursue research needed to understand it; to educate the public on the causes, risks, and hazards; and to communicate clearly and objectively with those who can implement policies to shape future climate.

PermIssions: Members everywhere are encouraged to help inform the policy making process in their home locales with thoughtful presentation of scientific viewpoints. Council adoption of position statements is one way that the Union can assist in this process. Any member may use an AGU policy statement in discussions with local or national policy makers as an official statement of the Union. If you use excerpts from a statement, then you should not attribute those as a Union position. Societies anywhere may use an AGU position statement with or without attribution as a basis for developing their own statements.

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### **GSA** Position Statement

Adopted October 2006; revised April 2010

### Climate Change

Position Statement. Decades of scientific research have shown that climate can change from both natural and anthropogenic causes. The Geological Society of America (GSA) concurs with assessments by the National Academies of Science (2005), the National Research Council (2006), and the Intergovernmental Panel on Climate Change (IPCC, 2007) that global climate has warmed and that human activities (mainly greenhouse-gas emissions) account for most of the warming since the middle 1900s. If current trends continue, the projected increase in global temperature by the end of the twenty-first century will result in large impacts on humans and other species. Addressing the challenges posed by climate change will require a combination of adaptation to the changes that are likely to occur and global reductions of CO<sub>2</sub> emissions from anthropogenic sources.

*Purpose*. This position statement (1) summarizes the strengthened basis for the conclusion that humans are a major factor responsible for recent global warming; (2) describes the large effects on humans and ecosystems if greenhouse-gas concentrations and global climate reach projected levels; and (3) provides information for policy decisions guiding mitigation and adaptation strategies designed to address the future impacts of anthropogenic warming.

### RATIONALE

Scientific advances in the first decade of the 21<sup>st</sup> century have greatly reduced previous uncertainties about the amplitude and causes of recent global warming. Ground-station measurements have shown a warming trend of ~0.7 °C since the mid-1800s, a trend consistent with (1) retreat of northern hemisphere snow and Arctic sea ice in the last 40 years; (2) greater heat storage in the ocean over the last 50 years; (3) retreat of most mountain glaciers since 1850; (4) an ongoing rise of global sea level for more than a century; and (5) proxy reconstructions of temperature change over past centuries from ice cores, tree rings, lake sediments, boreholes, cave deposits and corals. Both instrumental records and proxy indices from geologic sources show that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries (National Research Council, 2006).

Measurements from satellites, which began in 1979, initially did not show a warming trend, but later studies (Mears and Wentz, 2005; Santer et al., 2008) found that the satellite data had not been fully adjusted for losses of satellite elevation through time, differences in time of arrival over a given location, and removal of higher-elevation effects on the lower tropospheric signal. With these factors taken into account, the satellite data are now in basic agreement with ground-station data and confirm a warming trend since 1979. In a related study, Sherwood et al. (2005) found problems with corrections of tropical daytime radiosonde measurements and largely resolved a previous discrepancy with ground-station trends. With instrumental discrepancies having been resolved, recent warming of Earth's surface is now consistently supported by a wide range of measurements and proxies and is no longer open to serious challenge.

The geologic record contains unequivocal evidence of former climate change, including periods of greater warmth with limited polar ice, and colder intervals with more widespread glaciation. These and other changes were accompanied by major shifts in species and ecosystems. Paleoclimatic research has demonstrated that these major changes in climate and biota are associated with significant changes in climate forcing such as continental positions and topography, patterns of ocean circulation, the greenhouse gas composition of the atmosphere, and the distribution and amount of solar energy at the top of the atmosphere caused by changes in Earth's orbit and the evolution of the sun as a main sequence star. Cyclic changes in ice volume during glacial periods over the last three million years have been correlated to orbital cycles and changes in greenhouse gas concentrations, but may also reflect internal responses generated by large ice sheets. This rich history of Earth's climate has been used as one of several key sources of information for assessing the predictive capabilities

of modern climate models. The testing of increasingly sophisticated climate models by comparison to geologic proxies is continuing, leading to refinement of hypotheses and improved understanding of the drivers of past and current climate change.

Given the knowledge gained from paleoclimatic studies, several long-term causes of the current warming trend can be eliminated. Changes in Earth's tectonism and its orbit are far too slow to have played a significant role in a rapidly changing 150-year trend. At the other extreme, large volcanic eruptions have cooled global climate for a year or two, and El Niño episodes have warmed it for about a year, but neither factor dominates longer-term trends.

As a result, greenhouse gas concentrations, which can be influenced by human activities, and solar fluctuations are the principal remaining factors that could have changed rapidly enough and lasted long enough to explain the observed changes in global temperature. Although the 3rd IPCC report allowed that solar fluctuations might have contributed as much as 30% of the warming since 1850, subsequent observations of Sun-like stars (Foukal et al., 2004) and new simulations of the evolution of solar sources of irradiance variations (Wang et al., 2005) have reduced these estimates. The 4th (2007) IPCC report concluded that changes in solar irradiance, continuously measured by satellites since 1979, account for less than 10% of the last 150 years of warming.

Greenhouse gases remain as the major explanation. Climate model assessments of the natural and anthropogenic factors responsible for this warming conclude that rising anthropogenic emissions of greenhouse gases have been an increasingly important contributor since the mid-1800s and the major factor since the mid-1900s (Meehl et al., 2004). The CO<sub>2</sub> concentration in the atmosphere is now ~30% higher than peak levels that have been measured in ice cores spanning 800,000 years of age, and the methane concentration is 2.5 times higher. About half of Earth's warming has occurred through the basic heat-trapping effect of the gases in the absence of any feedback processes. This "clear-sky" response to climate is known with high certainty. The other half of the estimated warming results from the net effect of feedbacks in the climate system: a very large positive feedback from water vapor; a smaller positive feedback from snow and ice albedo; and sizeable, but still uncertain, negative feedbacks from clouds and aerosols. The vertical structure of observed changes in temperature and water vapor in the troposphere is consistent with the anthropogenic greenhouse-gas "fingerprint" simulated by climate models (Santer et al., 2008). Considered in isolation, the greenhouse-gas increases during the last 150 years would have caused a warming larger than that actually measured, but negative feedback from clouds and aerosols has offset part of the warming. In addition, because the oceans take decades to centuries to respond fully to climatic forcing, the climate system has yet to register the full effect of gas increases in recent decades.

These advances in scientific understanding of recent warming form the basis for projections of future changes. If greenhouse-gas emissions follow the current trajectory, by 2100 atmospheric CO2 concentrations will reach two to four times pre-industrial levels, for a total warming of less than 2 °C to more than 5 °C compared to 1850. This range of changes in greenhouse gas concentrations and temperature would substantially alter the functioning of the planet in many ways. The projected changes involve risk to humans and other species: (1) continued shrinking of Arctic sea ice with effects on native cultures and ice-dependent biota; (2) less snow accumulation and earlier melt in mountains, with reductions in spring and summer runoff for agricultural and municipal water; (3) disappearance of mountain glaciers and their latesummer runoff; (4) increased evaporation from farmland soils and stress on crops; (5) greater soil erosion due to increases in heavy convective summer rainfall; (6) longer fire seasons and increases in fire frequency; (7) severe insect outbreaks in vulnerable forests; (8) acidification of the global ocean; and (9) fundamental changes in the composition, functioning, and biodiversity of many terrestrial and marine ecosystems. In addition, melting of Greenland and West Antarctic ice (still highly uncertain as to amount), along with thermal expansion of seawater and melting of mountain glaciers and small ice caps, will cause substantial future sea-level rise along densely populated coastal regions, inundating farmland and dislocating large populations. Because large, abrupt climatic changes occurred within spans of just decades during previous ice-sheet fluctuations, the possibility exists for rapid future changes as ice sheets become vulnerable to large greenhouse-gas increases. Finally, carbon-climate model simulations indicate that 10-20% of the anthropogenic CO2 "pulse" could stay in

the atmosphere for thousands of years, extending the duration of fossil-fuel warming and its effects on humans and other species. The acidification of the global ocean and its effects on ocean life are projected to last for tens of thousands of years.

### PUBLIC POLICY ASPECTS

Recent scientific investigations have strengthened the case for policy action to reduce greenhouse gas emissions and to adapt to unavoidable climate change. To strengthen the consensus for action, this statement from the Geological Society of America is intended to inform policymakers about improved knowledge of Earth's climate system based on advances in climate science. Recent scientific investigations have contributed to this improved understanding of the climate system and supplied strong evidence for human-induced global warming, providing policy makers with a unique perspective on which to base mitigation and adaptation strategies. Carefully researched and tested adaptation strategies can both reduce and limit negative impacts and explore potential positive impacts. Future climate change will pose societal, biological, economic, and strategic challenges that will require a combination of national and international emissions reductions and adaptations. These challenges will also require balanced and thoughtful national and international discussions leading to careful long-term planning and sustained policy actions.

### RECOMMENDATIONS

- Public policy should include effective strategies for the reduction of greenhouse gas emissions. Cost-effective investments to improve the efficient use of Earth's energy resources can reduce the economic impacts of future adaptation efforts. Strategies for reducing greenhouse-gas emissions should be evaluated based on their impacts on climate, on costs to global and national economies, and on positive and negative impacts on the health, safety and welfare of humans and ecosystems.
- Comprehensive local, state, national and international planning is needed to address challenges posed by future climate change. Near-, mid-, and long-term strategies for mitigation of, and adaptation to climate change should be developed, based in part on knowledge gained from studies of previous environmental changes.
- Public investment is needed to improve our understanding of how climate change affects society, including on local and regional scales, and to formulate adaptation measures. Sustained support of climate-related research to advance understanding of the past and present operation of the climate system is needed, with particular focus on the major remaining uncertainties in understanding and predicting Earth's future climate at regional and global scales. Research is needed to improve our ability to assess the response and resilience of natural and human systems to past, present, and future changes in the climate system.

### ABOUT THE GEOLOGICAL SOCIETY OF AMERICA

The Geological Society of America, founded in 1888, is a scientific society with over 22,000 members from academia, government, and industry in more than 90 countries. Through its meetings, publications, and programs, GSA enhances the professional growth of its members and promotes the geosciences in the service of humankind. GSA encourages cooperative research among earth, life, planetary, and social scientists, fosters public dialogue on geoscience issues, and supports all levels of earth science education. Inquiries about the GSA or this position statement should be directed to GSA's 2009-2010 President, Dr. Jean M. Bahr, at +1-608-262-5513, or president@geosociety.org.

### OPPORTUNITIES FOR GSA AND ITS MEMBERS TO HELP IMPLEMENT RECOMMENDATIONS

To facilitate implementation of the goals of this position statement, the Geological Society of America recommends that its members take the following actions:

- Actively participate in professional education and discussion activities to be technically informed about the latest
  advances in climate science. GSA should encourage symposia at regional, national and international meetings to
  inform members on mainstream understanding among geoscientists and climate scientists of the causes and
  future effects of global warming within the broader context of natural variability. These symposia should seek to
  actively engage members in hosted discussions that clarify issues, possibly utilizing educational formats other than
  the traditional presentation and Q&A session.
- Engage in public education activities in the community, including the local level. Public education is a critical element of a proactive response to the challenges presented by global climate change. GSA members are encouraged to take an active part in outreach activities to educate the public at all levels (local, regional, national, and international) about the science of global warming and the importance of geological research in framing policy development. Such activities can include organizing and participating in community school activities; leading discussion groups in civic organizations; meeting with local and state community leaders and congressional staffs; participating in GSA's Congressional Visits Day; writing opinion pieces and letters to the editor for local and regional newspapers; contributing to online forums; and volunteering for organizations that support efforts to mitigate and adapt to global climate change.
- Collaborate with a wide range of stakeholders and help educate and inform them about the causes and impacts of
  global climate change from the geosciences perspective. GSA members are encouraged to discuss with businesses
  and policy makers the science of global warming, as well as opportunities for transitioning from our predominant
  dependence on fossil fuels to greater use of low-carbon energies and energy efficiencies.
- Work interactively with other science and policy societies to help inform the public and ensure that policymakers
  have access to scientifically reliable information. GSA should actively engage and collaborate with other earthscience organizations in recommending and formulating national and international strategies to address
  impending impacts of anthropogenic climate change.
- Take advantage of the following list of references for a current scientific assessment of global climate change.

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### PEER-REVIEWED ARTICLES

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### **SELECTED WEB SITES**

### INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

IPCC reports: www.ipcc.ch/

### U.S. NATIONAL ACADEMIES

Climate Change at the National Academies: dels.nas.edu/climatechange/

Surface temperature reconstructions: www.nap.edu/catalog.php?record\_id=11676#toc

### U.S. GLOBAL CHANGE RESEARCH PROGRAM

Home page: www.globalchange.gov/

Satellite issue: www.climatescience.gov/Library/sap/sap1-1/finalreport/default.htm

Geologic record of abrupt changes: www.climatescience.gov/Library/sap/sap3-4/final-report/

Global climate change impacts in the United States:

 $\underline{www.global change.gov./publications/reports/scientific-assessments/us-impacts}$ 

American Association for the Advancement of Science

American Chemical Society

American Geophysical Union

American Institute of Biological Sciences

American Meteorological Society

American Society of Agronomy

American Society of Plant Biologists

American Statistical Association

Association of Ecosystem Research Centers

Botanical Society of America

Crop Science Society of America

Ecological Society of America

Natural Science Collections Alliance

Organization of Biological Field Stations

Society for Industrial and Applied Mathematics

Society of Systematic Biologists

Soil Science Society of America

University Corporation for Atmospheric Research

### Dear Senator:

As you consider climate change legislation, we, as leaders of scientific organizations, write to state the consensus scientific view.

Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver. These conclusions are based on multiple independent lines of evidence, and contrary assertions are inconsistent with an objective assessment of the vast body of peer-reviewed science. Moreover, there is strong evidence that ongoing climate change will have broad impacts on society, including the global economy and on the environment. For the United States, climate change impacts include sea level rise for coastal states, greater threats of extreme weather events, and increased risk of regional water scarcity, urban heat waves, western wildfires, and the disturbance of biological systems throughout the country. The severity of climate change impacts is expected to increase substantially in the coming decades. <sup>1</sup>

If we are to avoid the most severe impacts of climate change, emissions of greenhouse gases must be dramatically reduced. In addition, adaptation will be necessary to address those impacts that are already unavoidable. Adaptation efforts include improved infrastructure design, more sustainable management of water and other natural resources, modified agricultural practices, and improved emergency responses to storms, floods, fires and heat waves.

We in the scientific community offer our assistance to inform your deliberations as you seek to address the impacts of climate change.

<sup>&</sup>lt;sup>1</sup> The conclusions in this paragraph reflect the scientific consensus represented by, for example, the Intergovernmental Panel on Climate Change and U.S. Global Change Research Program. Many scientific societies have endorsed these findings in their own statements, including the <u>American Association for the Advancement of Science, American Chemical Society, American Geophysical Union, American Meteorological Society, and American Statistical Association.</u>

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